PERGAMON

International Journal of Heat and Mass Transfer 43 (2000) 2573–2604

International Journal of
HEAT and MASS
TRANSFER

www.elsevier.com/locate/ijhmt

Critical heat flux (CHF) for water flow in tubes—I. Compilation and assessment of world CHF data

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Received 29 September 1998; received in revised form 24 May 1999

Abstract

The nuclear and conventional power industries have spent enormous resources during the past fifty years investigating the critical heat flux (CHF) phenomenon for a multitude of pool and flow boiling configurations. Experimental CHF data form the basis for the development of correlations and mechanistic models and comparison with them is the sole criterion for a reliable assessment of a correlation or model. However, experimental CHF data are rarely published, remaining in the archives of the authors or in obscure technical reports of an organization. The Purdue University-Boiling and Two-Phase Flow Laboratory (PU-BTPFL) CHF database for water flow in a uniformly heated tube was compiled from the world literature dating back to 1949 and represents the largest CHF database ever assembled with 32,544 data points from over 100 sources. The superiority of this database was proven via a detailed examination of previous databases. A point-by-point assessment of the PU-BTPFL CHF database revealed that 7% of the data were unacceptable mainly because these data were unreliable according to the original authors of the data, unknowingly duplicated, or in violation of an energy balance. Parametric ranges of the 30,398 acceptable CHF data were diameters from 0.25 to 44.7 mm, length-to-diameter ratios from 1.7 to 2484, mass velocities from 10 to 134,000 kg m^{-2} s^{-1}, pressures from 0.7 to 218 bars, inlet subcoolings from 0 to 347°C, inlet qualities from -3.00 to 0.00, outlet subcoolings from 0 to 305°C, outlet qualities from -2.25 to 1.00, and critical heat fluxes from 0.05×10^6 to 276×10^6 W m^{-2}. An examination of the parametric distribution of data within the database identified diameters less than 5 mm, mass velocities greater than 10,000 kg m^{-2} s^{-1}, and inlet qualities below -1.0 as those experimental conditions which at present have relatively little CHF data. The combination of these conditions most likely results in subcooled CHF conditions and relatively high CHF values. The PU-BTPFL CHF database is an invaluable tool for the development of CHF correlations and mechanistic models that are superior to existing ones developed with smaller, less comprehensive CHF databases.

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1. Introduction

Critical heat flux (CHF) or burnout refers to the sudden decrease in the heat transfer coefficient for a surface on which evaporation or boiling is occurring. Exceeding this heat flux causes the replacement of liquid adjacent to the heat transfer surface with a vapor blanket. This blanket acts as a barrier to heat flow from the heat dissipating device, resulting in possible catastrophic failure (burnout) of the device. The nuclear and conventional power industries have spent enormous resources during the past fifty years investigating the CHF phenomenon for a multitude of pool

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PII: S0017-9310(99)00191-X

Nomenclature

c_p	specific heat at constant pressure
D	inside diameter of tube
Fr_*	modified Froude number
g	gravitational acceleration
G	mass velocity
Ga	Galileo number, $D^3\rho_f(\rho_f-\rho_g)g/\mu_f^2$
h	enthalpy of fluid
h_f	enthalpy of saturated liquid
h_{fg}	latent heat of vaporization
K_{hor}	ratio of horizontal-to-vertical CHF for identical diameter, mass velocity, and pressure
L	heated length of tube
P	pressure
q_m	critical heat flux (CHF) defined using tube inside area
Re_D	Reynolds number, GD/μ_f
T	temperature
T_i	bulk liquid temperature at inlet
T_o	bulk liquid temperature at outlet (defined only if $x_o<0$)
ΔT_{sub}	liquid subcooling, $T_{sat}-T$, with saturation temperature evaluated at pressure associated with the CHF data point (usually outlet pressure)
x	thermodynamic equilibrium quality, $(h-h_f)/h_{fg}$, with saturated thermophysical properties evaluated at pressure associated with the CHF data point (usually outlet pressure)

Greek symbols

θ	tube inclination angle measured relative to the horizontal
μ	dynamic viscosity
ρ	density

Subscripts

f	liquid
g	vapor
i	inlet, beginning of heated length
o	outlet, end of heated length
sat	saturated conditions
sub	subcooled conditions

and flow boiling configurations. Investigators routinely conduct expensive experimental tests to ascertain the behavior of this phenomenon at specific operating conditions, often not realizing that similar tests had been conducted elsewhere. Experimental data form the basis for the development of CHF correlations and mechanistic (phenomenological) models and comparison with them is the sole criterion for a reliable assessment of a correlation or model. However, experimental CHF data are rarely published, remaining in the archives of the original authors or in obscure technical reports of an organization.

The present study was motivated by the lack of a large, reliable, error-free CHF database for developing correlations and mechanistic models to predict CHF in flow boiling. The objectives of the present study are the following: (1) examine all known CHF databases for imperfections, (2) compile all known CHF data obtained with vertical upflow or horizontal flow of water in a uniformly heated tube, (3) inspect this new CHF database on a point-by-point basis for erroneous data, and (4) minimize future research expenditures by (a) identifying those experimental conditions which at present have little or no CHF data and (b) recommending a methodology for acquiring CHF data in a manner that is useful in the development or refinement of CHF correlations and mechanistic models. The Purdue University-Boiling and Two-Phase Flow Laboratory (PU-BTPFL) CHF database was compiled by the present authors to achieve these goals and aid the nuclear power industry in their two-phase flow research. Part II [1] complements this study with (1) the compilation of all known subcooled CHF correlations for water flow in a uniformly heated tube, (2) the evaluation of these correlations using the CHF database from this study, and (3) the development of a simple, subcooled CHF correlation which is superior in accuracy to existing correlations and look-up tables.

2. Previous CHF databases

Experiments to determine the critical heat flux for water flow in uniformly heated, round tubes have been performed throughout the world during the past fifty years. The first compilation of CHF data was published by researchers at Westinghouse Electric Corp. [2] in 1958. Since then, twelve additional CHF databases (including the present study), each containing at least 1000 data points, have been described in the open literature. Table 1 lists these databases in chronological order along with the total number of CHF data points and the number of acceptable CHF data points. The number of acceptable CHF data points is the total number of CHF data points minus the number of invalid CHF data identified by the authors of the data-

Table 1
Summary of CHF databases for flow of water in a uniformly heated tube

Year	Organization	Abbreviation	Author(s)	Total CHF data points	Acceptable CHF data points[a]
1958	Westinghouse Electric Corp., Pittsburgh, PA	WAPD	DeBortoli et al. [2]	1013	992
1958	Knolls Atomic Power Laboratory, Schenectady, NY	KAPL	Ryan et al. [3]	1153	986
1960	Nuclear Development Corp. of America, White Plains, NY	NDA	Firstenberg et al. [4]	1034	878
1964	United Kingdom Atomic Energy Authority, Atomic Energy Establishment Winfrith, United Kingdom	UKAEA-AEEW	Thompson and Macbeth [5]	4372	3564
1964	Westinghouse Electric Corp., Pittsburgh, PA	WCAP	Tong et al. [6,7]	4730	4540
1985	Institute of Physics and Power Engineering, Obninsk, Russia	IPPE	Peskov [8]	8072	8067
1986	Atomic Energy of Canada Ltd., Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada University of Ottawa, Department of Mechanical Engineering, Ottawa, Ontario, Canada	AECL-UO	Groeneveld et al. [9]	15,442	13,026[b]
1992	United Kingdom Atomic Energy Authority, Atomic Energy Research Establishment, Harwell, United Kingdom	UKAEA-AERE	Govan and Hewitt [10]	4579	[c]
1992	Institute of Physics and Power Engineering, Heat and Mass Transfer Information Center, Obninsk, Russia	IPPE-HEMATIC	Kirillov et al. [11]	14,622	[c]
1993	National Committee for Nuclear Energy and Alternative Energy, Rome, Italy	ENEA	Celata and Mariani [12]	1865	1109
1996	Atomic Energy of Canada Ltd., Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada Institute of Physics and Power Engineering, Heat and Mass Transfer Information Center, Obninsk, Russia	AECL-IPPE	Groeneveld et al. [13]	29,005	21,897[b]
1996	Korea Advanced Institute of Science and Technology, Department of Nuclear Engineering, Taejon, South Korea	KAIST	Chang et al. [14], Moon et al. [15]	10,211	[c]
1998	Purdue University, Boiling and Two-Phase Flow Laboratory, West Lafayette, IN	PU-BTPFL	Hall and Mudawar (present study) [16–18]	32,544	30,398

[a] Acceptable CHF data points is the total number of CHF data points minus the number of invalid CHF data identified by the authors of the database or the authors of the present study. Data were deemed invalid if they were unreliable, duplicated in that database, incorrectly tabulated, or not obtained with vertical upflow or horizontal flow of water in a uniformly heated tube (see Refs. [16,17] for details).

[b] Superficial assessment of the database was conducted using the limited information provided in the reference.

[c] Assessment of the database was not conducted because detailed information was unavailable.

base or the authors of the present study. Data were deemed invalid if they were unreliable, duplicated in that database, incorrectly tabulated, or not obtained with vertical upflow or horizontal flow of water in a uniformly heated tube (see Refs. [16,17] for details). An assessment was usually not possible when the authors of the database did not provide tabulated CHF data. The authors of the present study consulted every source of data cited in each database in an attempt to determine the first publication of the data by the original authors of the data. Often, the source listed was not the original source of the data. The practice of obtaining CHF data from other databases and not the original source contributed to a majority of the imperfections found in the databases. The authors of the present study consulted the original source of the data in every possible case. Several of the more well-known CHF databases are discussed in the following sections.

2.1. Thompson and Macbeth CHF database

The CHF database cited most often in the literature was published in 1964 by Thompson and Macbeth of the United Kingdom Atomic Energy Authority [5]. The Tong et al. database [7] issued in the same year is similar in content to this database. Almost 30% (1246 data points) of the Thompson and Macbeth database was obtained directly from previously published databases [2,4] and not from the original authors of the data. Consequently, crucial information from the original data sources was omitted. Careful examination of the original publications containing the data illuminated the severe faults of the Thompson and Macbeth database. Sixty data points were obtained with test conditions other than flow of water in a uniformly heated tube (e.g., downflow, inclined flow, dissolved hydrogen or nitrogen in water). A limited point-by-point comparison of the database with original sources identified 228 data points that were in violation of an energy balance or tabulated with incorrect values of some parameters. Another 117 data points were identified by the present authors as unreliable for various reasons (e.g., severe flow rate and pressure fluctuations, intermittent flow reversal, visual CHF detection). All of these data were not indicated as such by Thompson and Macbeth. Also, the references cited by Thompson and Macbeth were in some cases incomplete, inaccurate, or omitted. The authorship of 342 data points could not be determined. Thus, the Thompson and Macbeth database contained only 3564 acceptable CHF data points; 18% fewer than the 4372 data points used by other researchers.

2.2. AECL-UO CHF database

Prior to the initiation of the present study, the largest CHF database described in the open literature was the one compiled by Groeneveld et al. [9] from Atomic Energy of Canada Limited (AECL) and University of Ottawa (UO). This proprietary database was unavailable to the present authors for an independent, point-by-point assessment of its contents. However, Groeneveld et al. provided the parametric ranges for each data source in the database so it was possible to conduct a preliminary assessment of the database. Only 5746 data points (37% of the database) were obtained from original sources; the majority of data were obtained from four previously published databases [5,7,8,19]. Consequently, nearly 2000 data points were unknowingly duplicated. By examining these other databases, the present authors identified another 354 data points that Groeneveld et al. tabulated incorrectly or did not realize were unreliable or for test conditions other than vertical upflow in a uniformly heated tube. The database mainly pertained to saturated CHF conditions with 103 data points even having a saturated inlet. The database contained approximately 1000 subcooled CHF data points and no data with a mass velocity above 7500 kg m^{-2} s^{-1}, conditions required for achieving high-CHF values.

2.3. ENEA CHF database

Recently, several subcooled CHF correlations [20–24] have been developed using a CHF database from the National Committee for Nuclear Energy and Alternative Energy (ENEA), Rome, Italy [12]. This database contains CHF data for various flow configurations but only for subcooled CHF conditions. Only 1354 of the 1865 data points were obtained with either vertical upflow or horizontal flow in a uniformly heated tube. The flow configuration for 267 data points was incorrectly labeled as vertical upflow in a uniformly heated tube when, in fact, the configuration was either horizontal flow (226 points), vertical downflow (39 points), or flow in a nonuniformly heated curved channel (2 points). Furthermore, a comparison of the database with the original data sources revealed that 245 data points were tabulated with incorrect values of some parameters. Only 59% of the data in the ENEA CHF database were correctly tabulated and obtained with either vertical upflow or horizontal flow in a uniformly heated round tube. Thus, correlations [20–24] developed or validated using the ENEA CHF database should be re-evaluated using a thoroughly inspected database for uniformly heated tubes.

Table 2
PU-BTPFL CHF database for (a) vertical upflow and (b) horizontal flow of water in a uniformly heated tube[a]

Reference	Total CHF data points	Unreliable data	Duplicate data	Energy balance violaton	$x_o > 1$	$x_i > 0$	$T_i \leq 0°C$	Acceptable CHF data points
(a) Vertical upflow								
McGill and Sibbitt [25]	38	1	0	–	0	0	0	37
Tramontini et al. [26][b]	61	0	0	–	0	0	0	61
Clark and Rohsenow [27]	89	0	0	47	0	0	0	42
Jens and Lottes [28]	34	0	0	10	0	0	0	24
Weatherhead and Lottes [29][c]	480	0	0	5	0	0	0	475
Hunt et al. [30]	93	0	0	0	0	0	0	93
Lowdermilk and Weiland [31]	155	155	0	–	0	0	0	0
Epstein et al. [32]	180	0	0	–	0	0	0	180
DeBortoli and Masnovi [33]	33	0	0	1	0	0	0	32
Longo [34]	20	0	0	–	0	0	0	20
Reynolds [35]	67	0	0	2	0	0	0	65
Lowdermilk et al. [36]	587	194	0	8	11	0	0	374
Ornatskii and Kichigin [37]	224	0	0	–	0	0	2	222
Peskov et al. [38]	264	0	0	14	0	0	0	250
Eicheldinger [39]	26	2	0	–	0	0	0	24
Hood and Isakoff [40]	28	0	0	–	0	0	0	28
Isakoff and Measley [41]	10	0	0	–	0	0	0	10
Ornatskii and Kichigin [42]	111	0	0	–	0	0	1	110
Swenson et al. [43]	25	0	0	0	0	0	0	25
Alessandrini et al. [44]	113	0	0	0	0	0	0	113
Lee and Obertelli [45]	609	7	0	0	0	0	0	602
Ornatskii [46]	69	0	0	–	0	0	2	67
Weatherhead [47]	232	0	0	0	0	0	0	232
Weatherhead [48]	62	20	0	–	0	4	0	38
Bertoletti et al. [49]	386	166	0	0	0	1	0	219
Peterlongo et al. [50]	313	0	0	0	0	1	0	312
Zenkevich et al. [51]	67	0	0	–	0	0	0	67
Becker et al. [52]	3473	0	0	22	0	0	0	3451
Bennett et al. [53]	201	0	0	0	0	0	0	201
Biancone et al. [54]	245	0	0	0	0	0	0	245
Burck and Hufschmidt [55]	143	0	0	0	0	0	0	143
Griffel [56]	402	0	0	0	0	0	0	402
Hewitt et al. [57]	442	0	0	0	4	15	0	423
Lee [58]	236	8	0	0	0	0	0	228
Matzner et al. [59]	104	18	0	0	0	0	0	86
Ornatskii and Vinyarskii [60]	109	0	0	–	0	0	13	96
Waters et al. [61]	38	0	0	0	0	0	0	38
Becker [62]	10	0	0	0	0	0	0	10
Era et al. [63]	84	0	0	0	0	0	0	84
Hassid et al. [64]	45	0	0	1	0	0	0	44
Judd et al. [65]	158	109	0	0	0	0	0	49
Lee [66]	437	0	0	0	0	0	0	437
Little and Trenberth [67]	13	0	0	0	0	0	0	13
Mayinger et al. [68]	1064	565	0	0	0	0	0	499
Bennett et al. [69]	12	0	0	–	0	0	0	12
Bergles et al. [70]	119	0	0	0	0	0	0	119
Fiori and Bergles [71]	19	0	0	–	0	0	0	19
Hassid et al. [72]	202	47	0	0	0	0	0	155
Babarin et al. [73]	163	0	0	–	49	0	0	114
Dell et al. [74]	81	0	0	0	0	0	0	81
Lee [75]	68	0	0	0	0	0	0	68
Becker [76]	160	0	0	32	0	0	0	128

(continued on next page)

Table 2 (*continued*)

Reference	Total CHF data points	Unreliable data	Duplicate data	Energy balance violaton	$x_o > 1$	$x_i > 0$	$T_i \leq 0°C$	Acceptable CHF data points
Becker and Ling [77]	87	0	0	0	5	0	0	82
Mihaila et al. [78]	149	0	149	0	0	0	0	0
Nilsson [79]	90	0	0	0	0	0	0	90
Nilsson [79]	62	0	0	0	0	0	0	62
Nilsson [79]	93	0	0	0	1	0	0	92
Nilsson [79]	44	0	0	0	0	0	0	44
Nilsson [79]	180	0	0	0	26	0	0	154
Nilsson [79]	53	0	53	0	0	0	0	0
Nilsson [79]	44	0	0	0	0	0	0	44
Nilsson [79]	22	0	0	0	0	0	0	22
Becker et al. [80]	1650	0	0	28	49	0	0	1573
Zenkevich et al. [81]	393	0	0	0	0	0	0	393
Campolunghi et al. [82]	218	0	0	–	2	0	0	216
Ceresa et al. [83]	167	0	0	0	36	0	0	131
Belyakov et al. [84][d]	585	0	0	10	0	0	0	575
Bailey [85]	19	0	0	–	0	0	0	19
Ladislau [86][d]	136	0	0	0	0	0	0	136
Bergel'son et al. [87][d]	336	0	0	0	0	0	0	336
Cumo et al. [88]	190	0	0	0	8	0	0	182
Smolin et al. [89]	3019	0	0	2	0	0	0	3017
Williams and Beus [90]	129	2	0	0	0	0	0	127
Kirillov et al. [91][d]	249	0	0	37	0	0	0	212
Kirillov et al. [91][d]	57	0	0	17	0	0	0	40
Kirillov et al. [91][d]	190	0	0	9	0	0	0	181
Kirillov et al. [91][d]	475	0	0	1	0	0	0	474
Kirillov et al. [91][d]	629	0	0	0	0	0	0	629
Kirillov et al. [91][d]	33	0	0	0	0	0	0	33
Kirillov et al. [91][d]	273	0	0	1	0	0	0	272
Kirillov et al. [91][d]	223	0	0	2	0	0	0	221
Kirillov et al. [91][d]	28	0	0	0	0	0	0	28
Kirillov et al. [91][d]	417	0	0	1	0	0	0	416
Mishima [92][e]	81	0	0	–	2	0	0	79
Peskov [8][d]	5700	0	0	29	0	0	0	5671
Peskov [8][d]	672	0	0	5	0	0	0	667
Peskov [8][d]	1117	0	0	5	0	0	0	1112
Nariai et al. [93][f]	95	0	0	0	0	0	0	95
Inasaka and Nariai [94]	29	0	0	0	0	0	0	29
Weber and Johannsen [95]	55	0	0	–	2	0	0	53
Inasaka et al. [96][f]	8	0	0	0	0	0	0	8
Nariai et al. [97][f]	7	0	0	–	0	0	0	7
Celata et al. [98][g]	60	0	0	–	0	0	0	60
Celata et al. [99]	43	0	0	–	0	0	0	43
Celata et al. [100]	78	0	0	–	0	0	0	78
Celata and Mariani [12]	87	0	0	–	0	0	0	87
Jafri [101]	21	0	0	–	0	7	0	14
Tain [102]	55	0	0	0	0	0	0	55
Vandervort et al. [24]	255	45	8	–	0	0	0	202
Celata [103]	41	0	0	–	0	0	0	41
Pabisz and Bergles [104]	10	0	0	–	0	0	0	10
Baek and Chang [105]	429	0	0	0	22	0	0	407
Mudawar and Bowers [106]	174	0	0	0	0	0	0	174
PU-BTPFL CHF database (vertical upflow)	31,661	1339	210	289	217	28	18	29560

Table 2 (*continued*)

Reference	Total CHF data points	Unreliable data	Duplicate data	Energy balance violaton	$x_o > 1$	$x_i > 0$	$T_i \leq 0°C$	Acceptable CHF data points
(b) Horizontal flow								
Gambill and Greene [107]	7	0	0	–	0	0	0	7
Gambill et al. [108]	24	0	0	0	0	0	0	24
Bergles and Rohsenow [109]	51	2	0	–	0	0	0	49
Bergles [110][h]	69	0	0	–	0	0	0	69
Dormer and Bergles [111]	13	0	0	–	0	0	0	13
Mayersak et al. [112]	1	0	0	–	0	0	0	1
Scarola [113][h]	9	0	0	–	0	0	1	8
Wessel [114][h]	34	0	0	–	0	0	2	32
Skinner and Loosmore [115]	111	12	0	–	0	0	1	98
Waters et al. [61]	26	0	0	0	0	0	0	26
Becker [116]	95	0	0	0	0	0	0	95
Ladislau [86][d]	257	0	0	0	0	0	0	257
Zeigarnik et al. [117]	28	0	0	–	0	0	8	20
Boyd et al. [118]	18	0	0	–	0	0	0	18
Boyd [119]	5	0	0	0	0	0	0	5
Boyd [120]	5	0	0	–	0	0	0	5
Boyd [121]	10	0	0	–	0	0	0	10
Gaspari and Cattadori [122]	33	0	0	–	0	0	0	33
Lezzi et al. [123]	87	0	0	0	0	19	0	68
PU-BTPFL CHF database (horizontal flow)	883	14	0	0	0	19	12	838

[a] Note:

Reference: Publication by the authors who obtained the CHF data. If CHF data were not tabulated in this reference, then one of the symbols above identifies the source of the data. Multiple rows are utilized for a single reference if the data were obtained at different experimental facilities.

Total CHF data points: CHF data obtained with flow of water subcooled at the inlet in a uniformly heated tube.

Unreliable CHF data: CHF data identified as invalid by either the original authors or authors of the present study (see Refs. [16,17] for details).

Duplicate data: CHF data appeared in another reference (see Refs. [16,17] for details).

Energy balance violation: Outlet quality tabulated in the reference differs by more than 0.05 (0.10 if pressure is greater than 75% of critical pressure) from outlet quality calculated by the authors of the present study using the tabulated inlet condition and an energy balance. A dash indicates that inlet and outlet conditions were not both tabulated and, thus, data were not verifiable using an energy balance. A zero indicates that all data satisfy an energy balance.

$x_o > 1$: Thermodynamic equilibrium outlet quality calculated using the tabulated inlet condition and an energy balance is greater than 1.00.

$x_i > 0$: Inlet quality calculated using saturated thermophysical properties based on outlet pressure is positive. Note that the inlet quality tabulated in the reference is negative since it is based on inlet pressure.

$T_i \leq 0°C$: Inlet temperature calculated using the tabulated outlet subcooling and an energy balance is less than 0°C.

Acceptable CHF data points: Total number of CHF data points minus the number of invalid CHF data indicated in the preceding columns.

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[b] Data obtained from Jens and Lottes [124].

[c] Data obtained from Roberts [125] and DeBortoli et al. [2].

[d] Data obtained from Smogalev [126].

[e] Data obtained from Baek and Chang [105].

[f] Data obtained from Inasaka [127].

[g] Data obtained from Celata and Mariani [12].

[h] Data obtained from Skinner and Loosmore [115].

2.4. AECL-IPPE CHF database

The Atomic Energy of Canada Limited (AECL) and the Institute of Physics and Power Engineering (IPPE), Obninsk, Russia merged their CHF databases [9,11] in order to develop a unified CHF database and look-up table [13]. In forming the largest CHF database cited in the world literature (prior to the present study), thousands of duplicate data points were overlooked. Both databases contained large portions of the Thompson and Macbeth database [5]. The IPPE database [11] combined an earlier IPPE database [8] with the rest of the known Russian CHF data and other data from the open literature. Also, an earlier version of Ref. [8] was incorporated into the AECL-UO database [9]. Consequently, the number of duplicate data points totaled nearly 6000. With the additional unusable data known to exist in the AECL-UO database (see discussion above), the maximum number of acceptable CHF data points was determined by the present authors to be no more than 21,897; 25% less than the 29,005 data points claimed to be in the database.

2.5. Summary

In order for a CHF database to be useful to other researchers, it must be both reliable and available in the open literature. None of the previous CHF databases satisfy these requirements. The abundance of duplicate and unusable data in previous databases prompted the authors of the present study to conduct an extensive literature search and compile all tabulated CHF data from the original sources. The validity of the data was also carefully examined on a point-by-point basis. Furthermore, the new database and detailed data assessment will be made available to the engineering community. Hopefully, other researchers will use this new database to develop the most accurate CHF correlations and mechanistic models possible.

3. Compilation of world CHF data

The contents of the PU-BTPFL CHF database are summarized in Table 2(a) and (b) for vertical upflow and horizontal flow water in a uniformly heated tube [8,12,24–123]. The reference cited is always the original source of the data. In a few cases, tabulated data were obtained from another publication by the authors of the data or by colleagues at the authors' institution. These cases are noted below the table. Multiple rows are utilized where a reference contained data obtained at several different experimental facilities. The authors of the present study did not attempt to collect CHF data presented only in graphical form. The PU-BTPFL CHF database is available in hard copy form as well as on CD-ROM [18].

Only CHF data obtained with vertical upflow or horizontal flow of water in a uniformly heated tube are included in the present database. The collection of data exclusively for these simple conditions provides a uniform database from which to develop correlations and models of the complex CHF phenomenon. Thus, CHF data obtained under the following experimental conditions were unconditionally excluded from the PU-BTPFL CHF database: nonaqueous fluid, deuterium oxide (heavy water), water with additives to enhance heat transfer, water with significant amounts of dissolved gas (e.g., hydrogen, nitrogen), noncircular channel (e.g., rectangular, annular, rod bundle), parallel-flow channel (two channels connected to same inlet plenum), nonuniform axial heat flux, nonuniform circumferential heat flux, vertical downflow, flow in an inclined tube, swirl flow promoter (e.g., twisted tape insert) within tube or upstream of tube inlet, abnormal test section inlet or outlet (e.g., orifice plate, inlet expansion, outlet contraction), active cooling of exterior surface of tube in addition to internal flow, applied magneto-electrical field or acoustical energy, and internal surface alterations to increase roughness and enhance heat transfer. Data obtained with a steam–water mixture at the tube inlet were also excluded because the liquid distribution over the entrance cross-section will depend on the method used for introducing the steam–water mixture and, consequently, influence CHF conditions. A list of references containing thousands of CHF data points obtained with vertical downflow or a steam–water mixture at the tube inlet as well as a list of other unusable CHF data not incorporated into the PU-BTPFL CHF database are given in Refs. [16,17].

A major weakness of previous CHF databases was the presence of a significant amount of duplicate data. The possibility of duplicate data in the PU-BTPFL CHF database was eliminated by careful inspection and by only consulting the original source of the data. A detailed list of references (not including the CHF databases previously discussed) containing CHF data identical to that in the reference (original data source) cited in the PU-BTPFL CHF database is provided in Refs. [16,17]. The fact that many of the references do not indicate the original source of the data should caution researchers from carelessly collecting data from the literature. This comprehensive list of CHF data sources should prevent the addition of duplicate data to the PU-BTPFL CHF database by other researchers.

4. Assessment of world CHF data

The experimental methods utilized by the researchers whose CHF data have been collected were thoroughly studied in order to substantiate the validity of their data. The test section characteristics, type of entrance region, type of water treatment, locations of pressure measurements, type of power supply, control parameter, and method of CHF detection are listed in Refs. [16,17] for each study. The importance of this information is described below. The classification of unreliable and duplicate data is briefly discussed with details provided in Refs. [16,17]. Other data were identified as unacceptable based on the results of an energy balance. Questionable data were also identified based on a thorough analysis of the subcooled portion of the database. This section concludes with a set of recommendations for obtaining accurate and useful CHF data that some researchers currently do not follow consistently.

4.1. Experimental methods

The test section material, orientation, wall thickness, surface roughness, and surface aging may have an effect on boiling heat transfer and CHF in flow boiling [128]. The surface roughness and aging of the tube wall were not described in most of the studies. Tube wall thickness for each individual data point is tabulated in the present study [18] where provided. The test section orientations and materials utilized in each study were also noted. Since tube wall thickness was often not reported and test section material was predominately stainless steel, insufficient data existed for a thorough investigation of these characteristics and their effect on CHF. The effect of tube orientation and flow direction on CHF is discussed in detail in a subsequent section.

The hydrodynamic development of the flow is dependent upon the flow loop configuration immediately upstream of the heated test section. If the test section is preceded by tubing having the same diameter as the test section, then an unheated entrance region exists. The length-to-diameter ratio of this region will determine if the flow is hydrodynamically fully developed before entering the heated region. On the contrary, if the heated length begins with an immediate contraction in flow area, then the hydrodynamic and thermal development of the flow begin at approximately the same axial location. Often, the flow was throttled using a valve located upstream of the unheated entrance region in order to eliminate pressure and flow rate fluctuations and insure stable operation of the flow loop. Only a minority of the studies provided information regarding the nature of the entrance region. Of those, most indicated the presence of some type of unheated entrance region, but not always of sufficient length to insure a fully developed flow upon entering the test section. Only a couple of the studies utilized a contraction at the entrance to the heated region.

The reported effects of dissolved gases in a fluid on CHF are rather contradictory [128]. Most researchers deaerate the liquid before conducting tests; however, the frequency of deaeration during the testing program was almost never mentioned. Typically, air was removed from the water by having vigorous boiling inside a large tank for an extended period of time, allowing noncondensable gases to escape to the atmosphere while condensing the water vapor. Frequently, the water was either deionized, demineralized, desalinated, and/or distilled before testing.

CHF for flow in a uniformly heated tube is generally believed to occur near the outlet. The majority of studies reported the outlet pressure with their CHF data. In those few cases where both inlet and outlet pressures were given, only the outlet pressure was tabulated with the CHF data in the present study [18]. All calculations performed in the present study utilized saturated thermophysical properties based on outlet pressure (unless only inlet pressure was given), except if inlet quality or subcooling was reported with both inlet and outlet pressures, then saturated thermophysical properties based on inlet pressure were required to calculate an inlet temperature. In almost every study, the pressure drop between the test section inlet and outlet and the difference between the pressure at the end of the heated length (outlet) and the pressure at the measurement location (usually downstream of the heated region) were not addressed. These pressure drops may be negligible except for high mass velocity flow in a small diameter tube when the measurement location is after an outlet expansion [106,129] or when a large distance exists between the end of the heated length and the measurement location. Furthermore, most studies provided little information, if any, regarding the exact location of the pressure measurement as well as the nature of the flow channel between the heated region and the measurement location. It was also unclear as to whether the tabulated outlet pressure corresponded to or was calculated (using a pressure drop model) from the pressure at the measurement location. The importance of an accurate outlet pressure cannot be overemphasized since saturated thermophysical properties used with CHF correlations and mechanistic models must often be evaluated at this pressure.

The test sections were always resistively heated (except that used in Ref. [95]) usually using dc current and electrodes at the inlet and outlet to the test section. Occasionally, ac current was utilized causing a slightly lower CHF than that occurring under identical testing conditions with dc current [108]. Power input to the test section at CHF was usually determined by measuring voltage across and current through the test section. In a few instances, Gambill et al. [108] and Celata and co-workers [12,98–100,103] inferred CHF from measured inlet and outlet fluid temperatures and an energy balance. As will be discussed in a subsequent section, this procedure should be avoided. In many cases, heat losses were either eliminated with insulation or shown to be relatively small; thus, a correction to the measured CHF was usually not needed.

CHF was usually approached by increasing power to the test section in small increments while maintaining constant flow rate, outlet pressure, and inlet temperature. Sometimes, test conditions near CHF were established and then either the inlet temperature was slowly increased or the flow rate decreased until CHF was detected. If the power, inlet temperature, or flow rate increments are small enough, then the CHF values obtained with the different methods should be consistent. The increments should also be relatively small so that the measured heat flux does not significantly overshoot the true CHF.

CHF detectors typically consisted of wires attached to the test section at the inlet and outlet electrodes and a wire attached to the tube near the outlet. The electrical resistance of the downstream section (between the two downstream wires) was compared with that of the upstream section in a Wheatstone bridge circuit. On inception of CHF, a sudden rise in wall temperature occurs causing the previously balanced bridge to become unbalanced and, consequently, disengaging the power supply. CHF was also detected by significant change in output of a thermocouple attached to the tube wall near the outlet. Usually, the thermocouple was electrically insulated from the tube using thin mica sheet and thermally insulated from the environment with glass wool. Sometimes, two thermocouples were used and positioned diametrically at the same axial location. Other times, the thermocouple was soldered to a small copper plate which was spring loaded against the tube wall near the outlet. In a few cases, several thermocouples were spaced along the tube near the outlet. In a few rare instances involving the same laboratory [44,49,50], the temperature excursion at CHF was indicated by melting of a zinc strip attached to the tube wall near the outlet. Occasionally, CHF was identified by the appearance of an incandescent spot on the tube wall near the outlet. If this qualitative visual observation was the sole method of CHF detection, then these data [31] were considered unreliable by the authors of the present study. The above methods of CHF detection preserved the test section and allowed multiple tests to be conducted with a single test section. The validity of a detection method was sometimes confirmed by increasing the heat flux past CHF (as indicated by the individual method used) until physical destruction (burnout) of the test section. Usually, the heat flux at burnout was at most a couple percent higher than the heat flux at which they defined CHF. Often, physical destruction of the test section was the only usable method for identifying subcooled CHF due to the much higher heat fluxes and inability of other methods to terminate power before damage to the test section occurred. In these cases, the test section was obviously used only once in contrast with the other detection methods.

4.2. Unreliable, duplicate, and corrected data

The number of unreliable and duplicate data points in each reference in the PU-BTPFL CHF database is given in Table 2(a) and (b). Each of these data points is noted as such in Ref. [18] with a detailed explanation given in Refs. [16,17]. In nearly every case, unreliable data were identified as such by the authors of the data and not by the authors of the present study. The authors of the present study did not label data unreliable by simply comparing data obtained from different data sources but at similar flow conditions and noting which data do not agree. Most of the unreliable data [31,36,39,48,49,58,68,72] were due to unstable flow conditions (flow rate and pressure fluctuations) producing a premature CHF. Sometimes, these data were not identified as such until a later publication by the authors of the data. Other unreliable data [24,49,65,90,109] were labeled as such by the authors of the data on the basis that CHF was lower than that of comparable data. Occasionally, inaccurate CHF measurements [59,115] were attributed to an unusual test section material. Duplicate data were discovered by the present authors during a thorough inspection of the data.

The authors of the present study corrected some data (see Refs. [16,17]) in the PU-BTPFL CHF database before the data were tabulated in Ref. [18]. Imperfections in the data were identified by comparing the parameter of the data point in question with a related parameter contained in a table or figure in the publication by the original authors or a related publication. For example, if the outlet quality violated an energy balance but the outlet subcooling satisfied the energy balance, then the outlet subcooling was assumed correct and the outlet quality was changed to reflect the outlet subcooling. Other pertinent comments concerning the data, which are too numerous and detailed to mention, are also given in Refs. [16,17].

4.3. Energy balance verification

The first law of thermodynamics requires that the energy content of a unit mass of fluid at the channel outlet (outlet enthalpy) equal the energy content at the inlet (inlet enthalpy) plus the energy added as the unit mass passes through the heated channel (heat input divided by mass flow rate),

$$h_{\mathrm{o}} = h_{\mathrm{i}} + 4\frac{L}{D}\frac{q_{\mathrm{m}}}{G}. \tag{1}$$

Eq. (1) is the only form of an energy balance utilized in the present study. Water was assumed an incompressible liquid, allowing saturated liquid enthalpy evaluated at the inlet temperature to approximate the inlet enthalpy of the subcooled liquid,

$$h_{\mathrm{i}} \cong h_{\mathrm{f}}(T_{\mathrm{i}}). \tag{2}$$

Thermodynamic equilibrium quality was always defined as

$$x = \frac{h - h_{\mathrm{f}}}{h_{\mathrm{fg}}} \tag{3}$$

with saturated liquid enthalpy and latent heat of vaporization evaluated at the pressure associated with the CHF data point (usually outlet pressure). The numerator of Eq. (3) was never replaced with the product of liquid specific heat and temperature subcooling. If the outlet was subcooled, then outlet temperature subcooling was defined as

$$\Delta T_{\mathrm{sub,o}} = T_{\mathrm{sat}} - T_{\mathrm{o}}, \tag{4}$$

where outlet bulk liquid temperature was determined by first calculating the outlet enthalpy from an energy balance and then, based on the assumption of an incompressible liquid, calculating outlet temperature from

$$h_{\mathrm{f}}(T_{\mathrm{o}}) \cong h_{\mathrm{o}} \tag{5}$$

using the secant method of iteration. The saturation temperature in Eq. (4) was evaluated at the pressure associated with the CHF data point (usually outlet pressure).

The calculation of fluid enthalpy, subcooling, and quality, as well as the development of CHF correlations and mechanistic models, requires accurate equations for the thermophysical properties of water. Equations for saturation temperature, saturated liquid density, saturated vapor density, saturated liquid enthalpy, and latent heat of vaporization were obtained from Irvine and Liley [130]. The type of equation utilized by Irvine and Liley was also discovered to accurately represent the variation of other properties. Refs. [16,17] provide equations for saturated liquid dynamic viscosity, saturated vapor dynamic viscosity, and saturated liquid thermal conductivity that were developed by the present authors from data in Haar et al. [131]. Refs. [16,17] also give an equation for saturated liquid specific heat that was developed from data given by Grigull et al. [132]. An equation for surface tension was obtained from Haar et al. All of these equations accurately predict the given property from the triple point to near the critical point of water.

CHF data from each reference listed in Table 2(a) and (b) were tabulated in a spreadsheet. If the tabulated inlet condition was inlet temperature subcooling, then inlet temperature was calculated by subtracting subcooling from saturation temperature based on inlet pressure (or outlet pressure if inlet pressure was not provided). But, if only inlet quality or inlet enthalpy subcooling were tabulated, then inlet temperature was found by first determining the inlet enthalpy. Also, if outlet quality or subcooling was tabulated instead of an inlet condition, then the outlet enthalpy was determined and inlet enthalpy calculated using Eq. (1). Once inlet enthalpy was determined, inlet temperature was calculated using Eq. (2) and the secant method of iteration. Finally, each CHF data point in the PU-BTPFL CHF database consisted of the following: tube inside diameter, heated length, mass velocity, outlet pressure (or inlet pressure if outlet pressure was not provided), inlet temperature, and measured CHF.

If both an inlet and outlet condition were provided in a study, then outlet quality was calculated using Eqs. (1) and (3) and the inlet temperature from the database. This calculated outlet quality was compared to outlet quality determined from the outlet condition tabulated by the authors of the data. If these outlet qualities differed by more than 0.05 (0.10 if the pressure was greater than 75% of the critical pressure), then an energy balance was violated and the data point was discarded from further analysis. The number of data points in each reference which violated an energy balance are indicated in Table 2(a) and (b). This procedure filtered the data for typographical errors introduced during the publication process or inaccurate thermophysical properties utilized by the authors of the data.

Other data in the PU-BTPFL CHF database which were excluded from further analysis included data which yielded a thermodynamic equilibrium outlet quality greater than 1.00 (indicating superheated steam), an inlet quality greater than 0.00 (indicating a steam–water mixture) when based on outlet pressure, or an inlet temperature less than 0°C (see discussion in next section). Table 2(a) and (b) list the number of these data points in each reference. Table 2(a) and (b) also indicate the total number of acceptable CHF data points in the PU-BTPFL CHF database as 29,560 (out of 31,661) and 838 (out of 883) for vertical upflow and horizontal flow, respectively. Nearly 7% of the database (2146 data points) was unacceptable mainly because the data were unreliable according to the original authors, duplicated, or in violation of an energy balance. The parameter ranges of the acceptable CHF data are given in Table 3(a) and (b) for vertical upflow and horizontal flow. The upper and lower number in each table cell represents the smallest and largest value, respectively, of that parameter for the acceptable CHF data in that reference. The last row in each table indicates the overall parametric range for data with that particular flow orientation.

4.4. Analysis of subcooled CHF data

Current and past research efforts of the present authors have focused on subcooled CHF [1,106,129,133]. The disclosure of the PU-BTPFL CHF database to the research community will allow others to investigate saturated CHF using a large, reliable CHF database. This section describes several irregularities discovered within the subcooled CHF data of the PU-BTPFL CHF database.

A large portion of the subcooled CHF data was the 513 data points published by Ornatskii and co-workers [37,42,46,60]. An inlet condition was not provided with these data. The present authors calculated the inlet temperature from the tabulated outlet subcooling using an energy balance (Eqs. (1) and (2)). This procedure yielded inlet temperatures as low as −34°C with 18 data points below 0°C. This impossible condition casts some doubt as to the accuracy of the tabulated outlet subcooling. Possibly, the outlet subcooling was calculated from a measured outlet temperature (see discussion below) or incorrect thermophysical properties produced a systematic error. Both situations could yield a tabulated outlet subcooling higher than the actual value. Thus, all data published by Ornatskii and co-workers should be utilized with caution. The same irregularity was also observed with 12 other data points [113–115,117].

The data from Ornatskii and Vinyarskii [60] were not tabulated with a specific value of the system pressure, but rather a pressure range over which a group of data were acquired. The measurement location corresponding to the pressure range was not given. Careful examination of the text and figures in Ref. [60] revealed that certain system pressures were dominant within each pressure range. The dominant pressure was always within 2 bars of the limits of the pressure range. These data were tabulated in the present study with this dominant pressure. The authors of the present study are unwilling to discard these unique data because they were obtained with small diameter tubes at high mass velocities and included the highest CHF value recorded prior to Mudawar and Bowers [106].

Celata and co-workers [12,98–100,103] utilized an atypical method of measuring the heat flux at CHF for their 309 subcooled data points. Celata [134] indicated that measured inlet and outlet temperatures at the instant of CHF were utilized to calculate CHF using an energy balance,

$$q_{\mathrm{m}} = \frac{GD}{4L} c_{\mathrm{pf}} (T_{\mathrm{o}} - T_{\mathrm{i}}), \tag{6}$$

where liquid specific heat was evaluated at the average of inlet and outlet bulk temperatures so that Eq. (6) approximates Eq. (1). Outlet temperature was measured downstream of the heated region after the fluid was mixed using a twisted tape over a length of 4 cm inside the tube. Mixing of the fluid was considered suitable by the investigators after a thermocouple traversed across the channel cross-section (diameter of 2.5–8.0 mm) indicated insignificant variations in temperature. The rationale behind this procedure was that significant heat losses precluded the calculation of power as the product of voltage across and current through the test section [98,100]. However, heat losses (axial conduction to electrodes and support structure and free convection and radiation to the environment) have been proven negligible compared to the heat dissipated to subcooled water flowing at similar mass velocities [135]. Celata [134] later indicated that tabulated values of power given by Celata et al. [99,100] were simply not reliable even though there was no mention of measurement inaccuracies. Celata's rationale for using a sensible energy balance instead of the more accurate and more widely used direct measurement of current and voltage ignores the following two possibilities. The mixing length downstream of the heated section (4 cm) was comparable to the length of the heated region (10 cm for the majority of tests) providing additional surface area for heat loss if, indeed, heat losses were significant for their apparatus. Insufficient mixing of the fluid or incomplete condensation of vapor generated in the heated section would lead to inaccurate temperature measurements. Both situations combine to produce a measured temperature of the flow core lower than the outlet temperature based on thermodynamic equilibrium, resulting in a calculated CHF lower than the actual value. Incidentally, CHF calculated from Eq. (6) and tabulated by Celata et al. [99,100] was from 30% higher to 30% lower than CHF calculated from measured power. In fact, calculations performed in the present study indicated that 22 of 43 CHF values [99] and 10 of 78 CHF values

Table 3
Parameter ranges of the acceptable CHF data for vertical upflow of water in a uniformly heated tube[a]

Reference	Acceptable CHF data	Tube dimensions				Inlet condition		Outlet condition		CHF
		$D \times 10^{-3}$ (m)	L/D	$G \times 10^{-3}$ (kg m^{-2} s^{-1})	$P \times 10^{-5}$ (N m^{-2})	$\Delta T_{sub,i}$ (°C)	x_i	$\Delta T_{sub,o}$ (°C)	x_o	$q_m \times 10^{-6}$ (W m^{-2})
(a) Vertical upflow										
McGill and Sibbitt [25]	37	3.6	20	1.2	20	4	−3.00	2	−2.25	3.4
		3.6	22	10.0	218	138	−0.02	86	0.29	13.3
Tramontini et al. [26][b]	61	5.7	109	1.2	34	21	−1.21	3	−0.46	1.6
		5.7	109	10.6	138	275	−0.08	91	0.51	11.9
Clark and Rohsenow [27]	42	4.6	52	0.01	7	21	−0.44		0.69	0.1
		4.6	52	0.10	138	158	−0.05		0.98	1.1
Jens and Lottes [28]	24	23.9	8	0.01	1	85	−0.16		0.24	0.2
		23.9	36	0.05	1	85	−0.16		0.83	0.9
Weatherhead and Lottes [29][c]	475	4.6	65	0.2	38	0	−0.65	1	−0.04	0.5
		7.8	76	8.6	138	201	0.00	6	0.80	6.8
Hunt et al. [30]	93	4.7	67	0.5	69	5	−1.30	1	−0.46	0.9
		4.7	67	10.5	138	297	−0.03	89	0.30	14.8
Lowdermilk and Weiland [31]	0									
Epstein et al. [32]	180	1.9	80	1.8	103	62	−2.43	0	−0.42	2.1
		1.9	365	4.2	190	338	−0.26	37	0.03	6.8
DeBortoli and Masnovi [33]	32	4.7	65	0.3	138	13	−0.65	1	−0.23	1.1
		4.7	65	5.7	138	134	−0.08	41	0.68	9.0
Longo [34]	20	5.3	38	3.1	1	24	−0.14	5	−0.05	2.1
		5.3	38	9.1	8	74	−0.05	26	−0.01	9.0
Reynolds [35]	65	4.6	50	1.2	36	3	−0.58	0	−0.13	3.6
		4.6	50	2.9	107	176	−0.01	39	0.50	9.0
Lowdermilk et al. [36]	374	1.3	25	0.03	1	75	−0.31	0	−0.03	0.2
		4.8	250	34.2	8	148	−0.14	17	0.99	41.6
Ornatskii and Kichigin [37]	222	2.0	20	5.0	10	15	−0.80	1	−0.65	6.4
		2.0	20	30.0	74	263	−0.04	212	0.00	70.9
Peskov et al. [38]	250	8.0	31	0.5	98	3	−1.12	12	−0.05	0.6
		8.0	262	5.5	196	273	−0.02	12	0.37	4.9
Eicheldinger [39]	24	10.6	36	0.7	69	64	−0.73		0.04	3.5
		10.6	72	1.5	83	227	−0.21		0.22	5.9
Hood and Isakoff [40]	28	8.0	26	0.7	69	13	−0.60	0	−0.03	3.2
		23.7	77	2.7	69	200	−0.04	9	0.48	5.3
Isakoff and Measley [41]	10	7.9	46	0.7	69	76	−0.48		0.02	3.3
		12.9	86	2.0	69	158	−0.24		0.42.	4.6
Ornatskii and Kichigin [42]	110	2.0	20	5.0	98	13	−1.54	6	−1.19	8.1
		2.0	20	30.0	147	333	−0.08	250	−0.03	72.1
Swenson et al. [43]	25	10.4	166	0.7	138	6	−0.52		0.18	0.6
		10.5	172	1.8	138	104	−0.04		0.51.	1.1
Alessandrini et al. [44]	113	15.2	32	1.1	48	16	−0.22	0	−0.04	1.7
		24.9	162	4.1	51	78	−0.05	14	0.53	3.7
Lee and Obertelli [45]	602	5.6	20	0.4	36	2	−0.56	0	−0.14	0.9
		11.5	359	4.4	111	158	−0.01	41	0.94	8.1
Ornatskii [46]	67	2.0	20	5.0	172	22	−2.47	4	−2.13	5.6
		2.0	20	30.0	196	347	−0.20	285	−0.04	70.4
Weatherhead [47]	232	7.7	41	0.2	138	0	−1.29	1	−0.82	0.8
		11.1	59	2.7	138	296	0.00	175	0.72	5.4
Weatherhead [48]	38	1.1	100	4.4	14	29	−0.32	2	−0.03	4.3
		1.1	100	15.7	14	146	−0.06	15	0.27	21.4
Bertoletti et al. [49]	219	4.9	10	1.1	49	0	−0.30		0.02	0.5
		15.2	546	3.9	99	89	0.00		0.77	7.5
Peterlongo et al. [50]	312	15.1	162	1.0	50	0	−0.63	1	−0.02	0.9
		15.2	273	4.0	66	236	0.00	7	0.63	4.1

(continued on next page)

Table 3 (*continued*)

Reference	Acceptable CHF data	Tube dimensions				Inlet condition		Outlet condition		CHF
		$D \times 10^{-3}$ (m)	L/D	$G \times 10^{-3}$ (kg m^{-2} s^{-1})	$P \times 10^{-5}$ (N m^{-2})	$\Delta T_{sub,i}$ (°C)	x_i	$\Delta T_{sub,o}$ (°C)	x_o	$q_m \times 10^{-6}$ (W m^{-2})
Zenkevich et al. [51]	67	6.8	10	0.6	39	51	−0.91	23	−0.21	4.9
		10.0	83	6.4	98	276	−0.20	53	−0.09	9.7
Becker et al. [52]	3451	3.9	40	0.1	2	19	−0.84	0	−0.07	0.3
		24.9	792	5.5	99	240	−0.04	27	1.00	7.5
Bennett et al. [53]	201	9.2	145	0.6	66	4	−0.46		0.02	0.6
		12.6	592	5.9	75	149	−0.01		0.96	3.3
Biancone et al. [54]	245	10.2	77	0.5	79	4	−1.28	0	−0.26	0.7
		17.1	102	3.2	144	289	−0.02	51	0.66	6.7
Burck and Hufschmidt [55]	143	10.0	35	0.9	11	125	−0.53	0	−0.25	4.5
		10.0	35	3.8	31	218	−0.27	101	0.09	12.2
Griffel [56]	402	6.2	26	0.6	34	9	−0.94	0	−0.21	1.4
		37.5	151	18.6	103	262	−0.03	65	0.59	8.1
Hewitt et al. [57]	423	9.3	25	0.09	1	0	−0.17		0.16	0.1
		9.3	328	0.30	2	91	0.00		1.00	4.0
Lee [58]	228	9.2	78	2.0	64	2	−0.26	0	0.00	1.0
		11.8	338	4.2	72	81	−0.01	0	0.46	4.3
Matzner et al. [59]	86	10.2	240	1.2	69	9	−0.48		0.01	0.6
		10.2	480	9.5	69	156	−0.03		0.64	4.2
Ornatskii and Vinyarskii [60]	96	0.5	28	20.0	10	75	−0.81	50	−0.57	39.5
		0.5	28	90.0	70	274	−0.16	188	−0.11	224.5
Waters et al. [61]	38	11.2	327	6.6	70	0	−0.82	1	−0.04	2.0
		11.2	327	9.6	104	226	0.00	9	0.34	5.4
Becker [62]	10	10.2	490	0.8	69	93	−0.41		0.33	0.7
		10.2	490	3.1	69	132	−0.30		0.84	1.5
Era et al. [63]	84	6.0	268	1.1	68	1	−0.41		0.37	0.4
		6.0	804	3.0	70	131	0.00		0.78	2.0
Hassid et al. [64]	44	15.1	104	1.1	50	2	−0.22		0.02	0.9
		15.1	263	3.9	70	69	−0.01		0.55	3.2
Judd et al. [65]	49	11.6	158	0.7	69	6	−0.68		0.01	0.6
		11.6	158	3.4	139	141	−0.03		0.76	2.7
Lee [66]	437	14.1	27	0.3	82	10	−0.39	0	−0.11	0.9
		44.7	108	3.4	126	83	−0.05	25	0.75	3.7
Little and Trenberth [67]	13	9.5	56	2.1	38	197	−0.51	18	−0.25	7.1
		9.5	56	9.5	39	199	−0.50	96	−0.05	18.3
Mayinger et al. [68]	499	7.0	5	0.9	19	0	−0.28	0	−0.19	0.9
		15.0	140	3.7	139	71	0.00	46	0.35	11.2
Bennett et al. [69]	12	12.6	290	0.4	69	13	−0.10		0.29	0.4
		12.6	441	3.9	69	30	−0.04		0.99	1.8
Bergles et al. [70]	119	9.7	63	0.1	34	19	−0.43	0	−0.02	0.7
		20.9	244	5.1	70	139	−0.07	5	0.98	6.0
Fiori and Bergles [71]	19	2.4	15	2.0	2	91	−0.27	11	−0.13	5.5
		6.1	30	9.1	6	135	−0.17	64	0.04	22.2
Hassid et al. [72]	155	24.9	63	0.4	29	1	−0.28	0	−0.02	1.4
		25.1	96	3.8	61	101	0.00	5	0.84	3.4
Babarin et al. [73]	114	12.0	80	0.05	3	9	−0.23		0.47	0.2
		12.0	150	0.50	3	118	−0.02		1.00	2.3
Dell et al. [74]	81	6.2	148	1.3	69	16	−0.24		0.14	0.5
		6.2	893	4.1	69	75	−0.05		0.76	3.3
Lee [75]	68	9.3	60	0.7	20	13	−0.49		0.22	0.8
		9.3	327	1.4	30	207	−0.03		0.83	3.8
Becker [76]	128	2.4	52	0.1	30	82	−0.71		0.20	1.1
		36.0	208	2.7	71	237	−0.21		0.90	5.1
Becker and Ling [77]	82	24.7	288	0.2	50	7	−0.33		0.26	0.2
		24.7	288	2.3	150	85	−0.02		1.00	1.3

Table 3 (*continued*)

Reference	Acceptable CHF data	Tube dimensions				Inlet condition		Outlet condition		CHF
		$D \times 10^{-3}$ (m)	L/D	$G \times 10^{-3}$ (kg m^{-2} s^{-1})	$P \times 10^{-5}$ (N m^{-2})	$\Delta T_{\mathrm{sub,i}}$ (°C)	x_{i}	$\Delta T_{\mathrm{sub,o}}$ (°C)	x_{o}	$q_{\mathrm{m}} \times 10^{-6}$ (W m^{-2})
Mihaila et al. [78]	0									
Nilsson [79]	90	10.0	200	0.3	30	9	−0.31		0.05	0.5
		10.0	200	4.8	89	96	−0.02		0.89	3.0
Nilsson [79]	62	10.0	198	0.6	70	12	−0.31		0.07	1.0
		10.0	198	4.0	70	96	−0.04		0.85	2.8
Nilsson [79]	92	10.0	199	0.2	29	5	−0.33		0.06	0.5
		10.0	199	6.0	92	106	−0.02		0.99	3.4
Nilsson [79]	44	10.0	200	0.4	70	3	−0.34		0.10	0.7
		10.0	200	3.2	91	96	−0.01		0.98	2.7
Nilsson [79]	154	9.9	202	0.6	30	10	−0.34		0.05	0.9
		9.9	202	6.0	90	102	−0.04		0.94	4.6
Nilsson [79]	0									
Nilsson [79]	44	9.9	202	0.4	64	6	−0.37		0.11	0.5
		9.9	202	3.4	70	119	−0.02		0.94	2.6
Nilsson [79]	22	9.4	214	1.0	67	2	−0.25		0.31	1.4
		9.4	214	3.4	70	76	−0.01		0.74	2.2
Becker et al. [80]	1573	10.0	100	0.2	30	5	−2.47	0	−0.91	0.1
		10.0	497	8.1	200	272	−0.02	74	1.00	5.5
Zenkevich et al. [81]	393	7.8	897	1.0	69	3	−1.92		0.25	0.05
		8.1	2484	2.8	176	315	−0.01		0.88	1.3
Campolunghi et al. [82]	216	12.0	1833	1.1	55	29	−0.80		0.38	0.2
		12.0	1833	2.5	166	130	−0.10		0.99	0.5
Ceresa et al. [83]	131	4.9	232	0.2	48	13	−0.52		0.15	0.1
		7.9	1230	3.0	51	193	−0.04		1.00	3.5
Belyakov et al. [84][d]	575	20.0	150	0.3	104	0	−2.00	0	−0.35	0.1
		40.0	401	1.9	210	247	0.00	22	0.87	1.2
Bailey [85]	19	15.0	361	0.08	14	10	−0.26		0.45	0.1
		15.0	361	1.4	70	110	−0.02		0.97	1.1
Ladislau [86][d]	136	4.0	50	0.9	4	24	−0.32	4	−0.05	1.9
		4.0	50	5.5	10	150	−0.05	25	−0.01	4.6
Bergel'son et al. [87][d]	336	8.0	30	1.9	2	22	−0.48	0	−0.30	3.5
		8.0	50	7.1	31	197	−0.05	129	0.09	14.6
Cumo et al. [88]	182	12.9	620	0.3	67	18	−0.35		0.45	0.2
		12.9	766	2.0	74	110	−0.06		1.00	0.9
Smolin et al. [89]	3017	3.8	86	0.5	29	1	−1.75	0	−0.18	0.2
		16.0	756	7.7	177	281	0.00	18	0.76	5.6
Williams and Beus [90]	127	9.5	193	0.3	28	21	−1.25	0	−0.03	0.4
		9.5	193	4.7	152	252	−0.12	5	0.93	4.1
Kirillov et al. [91][d]	212	7.8	130	0.5	68	8	−1.84	0	−0.26	0.4
		7.8	384	4.0	180	300	−0.03	28	0.83	5.1
Kirillov et al. [91][d]	40	8.0	125	1.0	98	4	−1.74	1	−0.45	1.0
		8.0	125	4.0	176	280	−0.03	54	0.48	3.7
Kirillov et al. [91][d]	181	8.0	126	1.0	69	5	−1.84	1	−0.51	0.5
		8.0	377	4.0	176	300	−0.02	62	0.53	7.7
Kirillov et al. [91][d]	474	8.0	125	0.5	69	1	−1.78	0	−0.48	0.2
		8.0	375	4.0	176	287	0.00	59	0.96	5.9
Kirillov et al. [91][d]	629	8.0	124	0.5	68	1	−1.99	0	−0.43	0.1
		8.1	749	4.1	180	310	0.00	51	0.97	6.2
Kirillov et al. [91][d]	33	8.0	377	2.0	98	23	−0.71		0.08	1.0
		8.0	377	4.1	137	201	−0.12		0.38	2.2
Kirillov et al. [91][d]	272	7.8	125	1.0	69	20	−0.92	0	−0.04	0.2
		8.0	769	4.0	137	200	−0.07	6	0.75	3.6
Kirillov et al. [91][d]	221	8.0	125	0.5	69	7	−1.52	1	−0.33	0.3
		8.0	375	2.1	178	237	−0.03	37	0.98	3.8

(*continued on next page*)

Table 3 (*continued*)

Reference	Acceptable CHF data	Tube dimensions				Inlet condition		Outlet condition		CHF
		$D \times 10^{-3}$ (m)	L/D	$G \times 10^{-3}$ (kg m^{-2} s^{-1})	$P \times 10^{-5}$ (N m^{-2})	$\Delta T_{\mathrm{sub,i}}$ (°C)	x_{i}	$\Delta T_{\mathrm{sub,o}}$ (°C)	x_{o}	$q_{\mathrm{m}} \times 10^{-6}$ (W m^{-2})
Kirillov et al. [91][d]	28	8.0	125	2.0	69	34	−1.08	8	−0.13	2.1
		8.0	125	2.0	137	242	−0.11	23	0.29	4.1
Kirillov et al. [91][d]	416	7.7	127	1.0	64	9	−1.83	5	−0.07	0.2
		7.8	778	4.2	180	293	−0.04	16	0.82	5.0
Mishima [92][e]	79	6.0	57	0.01	1	20	−0.13	2	−0.01	0.1
		6.0	57	1.8	1	70	−0.04	5	0.99	2.1
Peskov [8][d]	5671	4.0	29	0.5	59	0	−2.63	0	−1.69	0.1
		15.1	1026	9.9	196	325	0.00	186	0.95	14.8
Peskov [8][d]	667	3.8	96	0.5	78	1	−2.13	0	−0.13	0.2
		10.8	514	7.6	196	256	0.00	15	0.78	5.7
Peskov [8][d]	1112	10.0	100	0.2	98	9	−2.24	0	−0.82	0.1
		10.0	497	7.6	196	267	−0.05	74	0.94	5.0
Nariai et al. [93][f]	95	1.0	3	6.7	1	36	−0.16	3	−0.13	4.7
		3.0	50	20.9	1	85	−0.07	72	0.01	70.0
Inasaka and Nariai [94]	29	3.0	33	4.3	3	63	−0.31	20	−0.18	7.3
		3.0	33	29.9	10	150	−0.12	87	−0.04	44.5
Weber and Johannsen [95]	53	10.0	4	0.02	1	3	−0.21		0.09	1.5
		10.0	4	0.30	12	100	−0.01		0.80	7.6
Inasaka et al. [96][f]	8	6.0	17	6.5	1	59	−0.12	42	−0.09	7.3
		6.0	17	11.4	1	63	−0.11	48	−0.08	11.2
Nariai et al. [97][f]	7	6.0	17	7.7	2	73	−0.32	50	−0.24	12.1
		6.0	17	10.0	15	144	−0.14	109	−0.10	17.2
Celata et al. [98][g]	60	6.0	12	2.0	4	83	−0.62	54	−0.52	7.4
		8.0	19	10.1	51	232	−0.16	193	−0.11	29.5
Celata et al. [99]	43	2.5	20	2.2	1	79	−0.44	19	−0.26	4.0
		5.0	40	32.6	22	194	−0.15	113	−0.03	42.8
Celata et al. [100]	78	2.5	40	11.2	6	92	−0.46	52	−0.36	12.1
		2.5	40	40.0	26	196	−0.19	150	−0.11	60.6
Celata and Mariani [12]	87	2.5	20	2.9	1	80	−0.46	23	−0.36	6.9
		5.0	40	43.1	26	196	−0.15	155	−0.04	56.8
Jafri [101]	14	15.7	155	1.5	4	0	−0.23		0.09	2.3
		15.7	155	7.8	11	106	0.00		0.43	5.6
Tain [102]	55	8.0	219	2.4	68	5	−0.31		0.03	1.3
		8.0	219	7.8	101	95	−0.02		0.38	4.4
Vandervort et al. [24]	202	0.33	2	8.4	1	40	−0.39	10	−0.28	18.7
		2.7	26	41.8	23	183	−0.08	130	−0.02	123.8
Celata [103]	41	0.25	40	7.3	1	69	−0.33	9	−0.22	10.2
		1.5	40	49.7	9	156	−0.13	104	−0.02	67.6
Pabisz and Bergles [104]	10	4.4	25	2.4	6	133	−0.35	64	−0.20	7.4
		6.2	25	5.0	13	113	−0.28	91	−0.13	13.9
Baek and Chang [105]	407	6.0	50	0.03	1	15	−0.31		0.32	0.1
		10.0	167	0.3	10	149	−0.03		1.00	1.5
Mudawar and Bowers [106]	174	0.41	2	5.0	3	61	−1.90	32	−1.78	9.4
		2.5	34	134.0	172	329	−0.12	305	−0.06	276.0
PU-BTPFL CHF database (vertical upflow)	29,560	0.25	2	0.01	1	0	−3.00	0	−2.25	0.05
		44.7	2484	134.0	218	347	0.00	305	1.00	276.0
(b) Horizontal flow										
Gambill and Greene [107]	7	7.7	6	13.1	1	64	−0.18	57	−0.16	15.8
		7.7	20	26.1	1	95	−0.12	88	−0.11	33.1
Gambill et al. [108]	24	3.2	7	7.1	0.7	76	−0.28	10	−0.24	7.0
		7.0	88	52.8	5	141	−0.14	122	−0.02	54.4

Table 3 (*continued*)

Reference	Acceptable CHF data	Tube dimensions				Inlet condition		Outlet condition		CHF
		$D \times 10^{-3}$ (m)	L/D	$G \times 10^{-3}$ (kg $\mathrm{m^{-2}\ s^{-1}}$)	$P \times 10^{-5}$ (N $\mathrm{m^{-2}}$)	$\Delta T_{\mathrm{sub,i}}$ (°C)	x_{i}	$\Delta T_{\mathrm{sub,o}}$ (°C)	x_{o}	$q_{\mathrm{m}} \times 10^{-6}$ (W $\mathrm{m^{-2}}$)
Bergles and Rohsenow [109]	49	0.6	5	3.0	2	25	−0.22	1	−0.08	6.0
		4.6	50	6.1	2	115	−0.05	44	0.05	25.1
Bergles [110][h]	69	1.2	13	1.5	1	14	−0.22	3	−0.14	5.1
		6.1	49	24.3	6	113	−0.03	71	0.09	44.8
Dormer and Bergles [111]	13	2.4	23	3.0	2	67	−0.24	6	−0.12	5.6
		4.6	52	12.2	6	119	−0.13	60	0.00	18.0
Mayersak et al. [112]	1	11.7	50	45.4	29	213	−0.51	168	−0.40	42.9
		11.7	50	45.4	29	213	−0.51	168	−0.40	42.9
Scarola [113][h]	8	1.2	27	3.0	2	51	−0.28	2	−0.06	6.2
		6.2	27	6.1	4	140	−0.10	34	0.00	13.0
Wessel [114][h]	32	6.1	15	1.5	2	46	−0.20	7	−0.09	3.2
		7.8	35	6.1	2	102	−0.09	47	−0.01	9.8
Skinner and Loosmore [115]	98	1.2	3	5.0	2	28	−0.32	1	−0.24	6.6
		6.1	52	20.0	7	158	−0.06	120	0.00	33.4
Waters et al. [61]	26	11.2	327	6.5	104	4	−0.72	1	−0.03	2.0
		11.2	327	9.6	104	196	−0.02	7	0.37	4.8
Becker [116]	95	10.0	74	0.2	9	60	−0.48		0.24	0.8
		12.9	96	1.7	31	199	−0.14		0.75	4.1
Ladislau [86][i]	257	4.0	50	0.9	2	29	−0.34	2	−0.06	1.2
		4.0	50	6.5	16	153	−0.06	30	−0.01	5.8
Zeigarnik et al. [117]	20	4.0	62	4.8	5	80	−0.51	25	−0.22	9.4
		4.0	62	20.6	30	215	−0.19	93	−0.06	32.6
Boyd et al. [118]	18	10.2	116	0.8	16	181	−0.40	7	−0.10	1.4
		10.2	116	3.4	16	181	−0.40	43	0.10	4.3
Boyd [119]	5	3.0	97	4.6	8	149	−0.31	24	−0.12	6.3
		3.0	97	40.6	8	149	−0.31	57	−0.05	41.6
Boyd [120]	5	3.0	97	4.4	17	183	−0.41	51	−0.18	6.4
		3.0	97	31.5	17	183	−0.41	78	−0.12	36.2
Boyd [121]	10	10.2	49	1.6	4	128	−0.25	35	−0.13	2.4
		10.2	49	7.5	4	128	−0.25	64	−0.07	11.5
Gaspari and Cattadori [122]	33	8.0	15	4.6	10	110	−0.52	83	−0.42	11.0
		15.0	20	14.9	55	186	−0.23	151	−0.18	35.6
Lezzi et al. [123]	68	1.0	239	0.8	29	0	−0.65		0.64	0.3
		1.0	975	2.7	72	241	0.00		0.98	2.4
PU-BTPFL CHF database (horizontal flow)	838	0.6	3	0.2	0.7	0	−0.72	1	−0.42	0.3
		15.0	975	52.8	104	241	0.00	168	0.98	54.4

[a] Note:

Reference column identifies the publication by the authors who obtained the CHF data. If CHF data were not tabulated in this reference, then one of the symbols above identifies the source of the data. Multiple rows were utilized for a single reference if the data were obtained at different experimental facilities.

The upper and lower number in each cell of a parameter column represent the smallest and largest value, respectively, of that parameter for the acceptable CHF data in that reference. Outlet conditions were calculated using the inlet temperature from the database and an energy balance. Saturated thermophysical properties were evaluated at the pressure associated with the CHF data point (usually outlet pressure).

[b] Data obtained from Jens and Lottes [124].

[c] Data obtained from Roberts [125] and DeBortoli et al. [2].

[d] Data obtained from Smogalev [126].

[e] Data obtained from Baek and Chang [105].

[f] Data obtained from Inasaka [127].

[g] Data obtained from Celata and Mariani [12].

[h] Data obtained from Skinner and Loosmore [115].

[i] Data obtained from Smogalev [126].

[100] were larger than the maximum possible heat flux based on the tabulated power. Data given by Celata et al. [98] and Celata and Mariani [12] did not contain power measurements and, hence, could not be inspected for this irregularity. To the best of the present authors' knowledge, the data given by Celata and co-workers [12,98–100,103] and Gambill et al. [108] were the only data in the PU-BTPFL CHF database with CHF determined using a sensible energy balance (Eq. (6)).

Over 18% of the CHF data obtained by Vandervort et al. [24] was labeled as premature CHF with the justification that capillary tubes having a diameter less than 2.5 mm had a smooth internal surface creating nucleation instabilities, that tube burnout occurred in the upstream portion of the tube, and that measured CHF was lower than CHF predicted by their correlation. Vandervort [136] also noted that premature CHF occurred when a solenoid valve in their flow loop was cycled causing a 'significant mechanical shock to the system'. None of these phenomena were reported by Nariai et al. [93], Inasaka and Nariai [94], Celata and co-workers [12,99,100,103], and Mudawar and Bowers [106] who obtained measurements under similar operating conditions. The test section fabrication procedure or the experimental apparatus employed by Vandervort et al. [24] may be causing these premature failures. Thus, even the data labeled as non-premature CHF by Vandervort et al. must be used with caution.

While some of the irregularities described above are quite serious, the present authors recommend only that these subcooled CHF data be used with caution. The data in question represent most of the small diameter, high mass velocity, high-CHF data in the PU-BTPFL CHF database. Their exclusion would severely limit the usefulness of the database in the development and assessment of subcooled CHF correlations such as those in Part II [1] of the present study. Hopefully, the saturated CHF data in the database will be examined with similar scrutiny by others in the research community.

4.5. Recommendations

This detailed assessment of the data in the PU-BTPFL CHF database illuminated key mistakes committed by some researchers. The present authors propose the following procedures for acquiring and publishing useful CHF data:

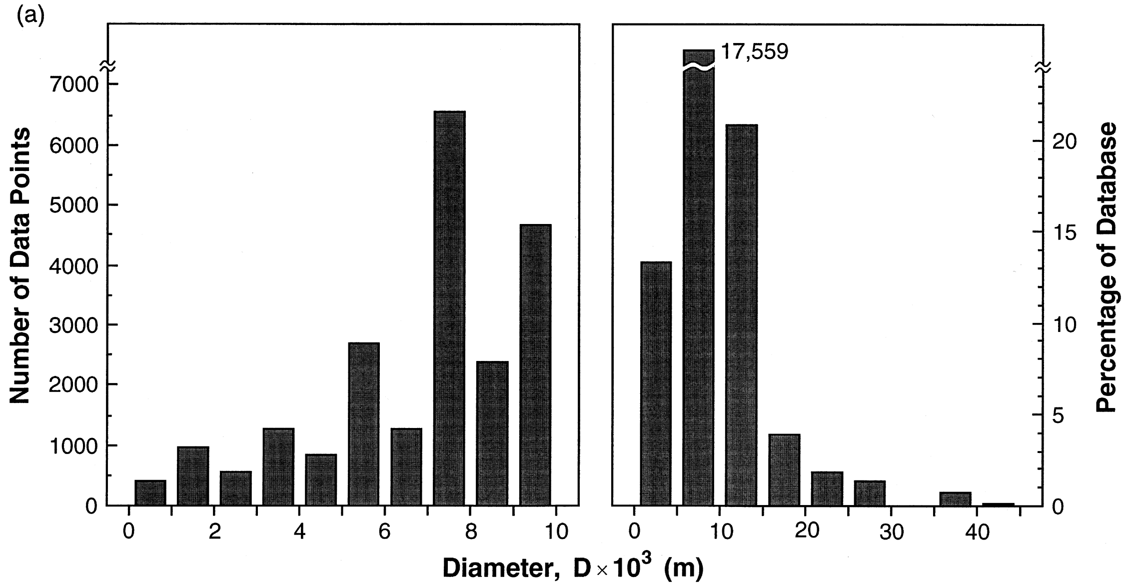
1. The possibility of premature CHF must be eliminated from an experimental apparatus prior to acquiring useful and accurate data. The fabrication and installation of test sections must be done with extreme care so as not to promote premature CHF. Other causes of premature CHF include flow rate oscillations, fast increase of heater power, or fast decrease of flow rate.
2. An unheated entrance region, having the same diameter as the test section and a length long enough to insure that the flow is hydrodynamically developed prior to entering the heated region, should be utilized so that data from different researchers are consistent. An abrupt contraction should be avoided since this may affect CHF for relatively short tubes.
3. Test sections should always be resistively heated with dc current. Measured CHF must be determined from the voltage across and current through the test section. The calculation of CHF from measured inlet and outlet fluid temperatures is not recommended. Heat losses should be minimized so that a correction to the measured CHF is not needed. Heat losses should not be neglected without a detailed analysis.
4. Detailed operating conditions for each CHF data point must be tabulated. Nomenclature should be clearly defined. Test section material and tube wall thickness should be indicated for each data point.
5. Inlet and outlet pressure should be measured as close as possible to the beginning and end, respectively, of the heated length. Both measurements should be tabulated with the CHF data. The flow channel between measurement location and heated region should be described. Ideally, this flow channel should have the same diameter as that of the heated region. If a pressure drop model is utilized to calculate outlet (or inlet) pressure from a downstream (or upstream) measurement, then the model should be presented in detail.
6. Both inlet temperature and either outlet quality or subcooling should be tabulated. The outlet condition must be calculated from an energy balance based on fluid enthalpy (not specific heat which varies with pressure). This allows other researchers to detect typographical errors committed during the publication process.
7. The experimental program should be carefully outlined prior to testing in order to minimize the number of data points acquired within a range of operating conditions. Data should not be taken at random conditions. Furthermore, the inspection of the data should readily yield the parametric trends.

5. Parametric distribution of world CHF data

All CHF data for vertical upflow and horizontal flow in a uniformly heated round tube are tabulated in Ref. [18]. This database, known as the PU-

BTPFL CHF database, contains over 30,000 experimental CHF data points; the largest database available to the research community in hard copy form as well as on CD-ROM. This section focuses on identifying those operating conditions where few CHF data points exist.

Fig. 1(a)–(h) show the distribution of data within the database based on diameter, heated length-to-diameter ratio, mass velocity, pressure, inlet subcooling, inlet quality, outlet quality, and critical heat flux, respectively. Two bar charts are shown for each parameter except inlet subcooling. The main bar chart shows the distribution of data over the entire range of that parameter. The secondary bar chart shows the distribution of data over a much smaller range corresponding to the longest bars from the main chart. Data points obtained with a value of a parameter corresponding to the upper boundary of a bin are always included within that bin. In some cases, the number of data points within a bin is so small that a bar is not



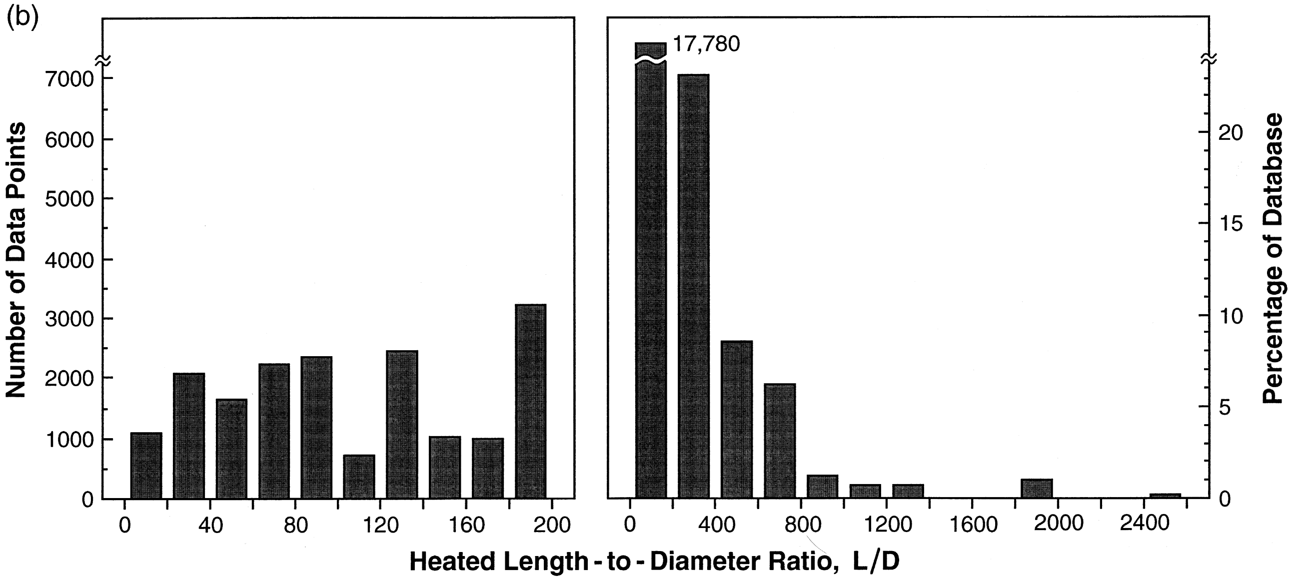


Fig. 1. Distribution of data within PU-BTPFL CHF database: (a) diameter, (b) heated length-to-diameter ratio, (c) mass velocity, (d) pressure, (e) inlet subcooling, (f) inlet quality, (g) outlet quality, and (h) critical heat flux.

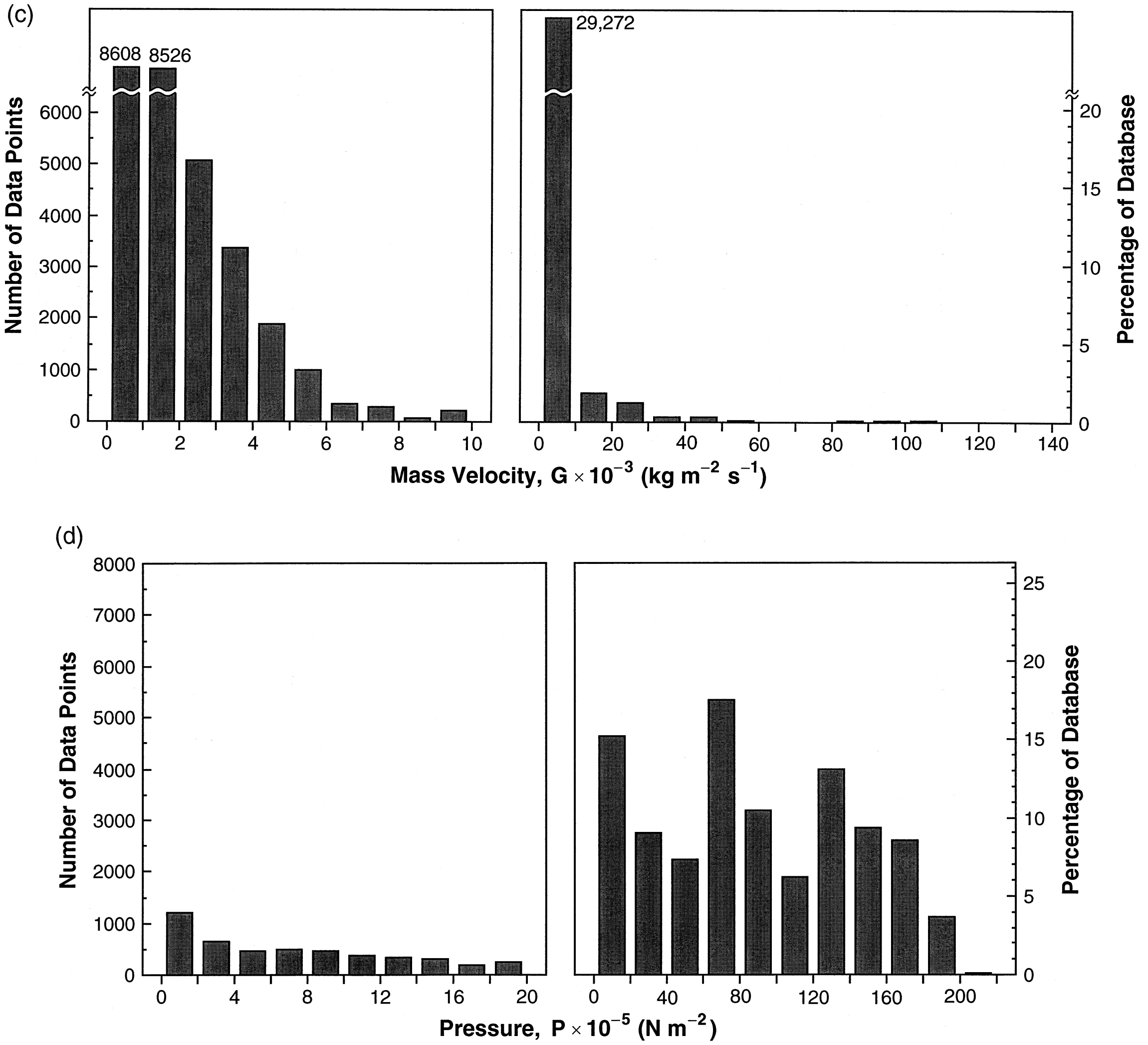


Fig. 1 (*continued*)

visible. In other cases, the number of data points within a bin exceeds the maximum value of the ordinate and must be noted next to the bar. Based on the main bar chart, approximately 95% of the data were obtained within the following ranges: $D < 20 \times 10^{-3}$ m, $L/D < 800$, $G < 10{,}000$ kg m^{-2} s^{-1}, $P < 180 \times 10^5$ N m^{-2}, $\Delta T_{\mathrm{sub,i}} < 220°\mathrm{C}$, $x_\mathrm{i} > -1.5$, $x_\mathrm{o} > -0.5$, and $q_\mathrm{m} < 20 \times 10^6$ W m^{-2}. In an effort to minimize research expenditures, the authors of the present study recommend that future experimental programs focus on the following conditions:

1. small diameter tubes ($D < 5 \times 10^{-3}$ m),
2. high mass velocities ($G > 10{,}000$ kg m^{-2} s^{-1}), and
3. low inlet qualities ($x_\mathrm{i} < -1.0$) with correspondingly low outlet qualities.

The combination of these conditions will most likely yield a subcooled outlet with high-CHF values.

Fig. 2(a)–(f) shows the distribution of data in two-dimensional scatter plots using the six possible combinations of the local conditions parameters (diameter, mass velocity, pressure, and outlet quality). Each symbol represents one of the 30,398 acceptable CHF data points displayed within each plot. Dense regions in the plots may consist of many overlapping data points. Careful examination of these plots reveals the following:

1. diameters above 10 mm are associated with low mass velocities ($G < 10{,}000$ kg m^{-2} s^{-1}),
2. mass velocities above 20,000 kg m^{-2} s^{-1} require small diameter tubes ($D < 5 \times 10^{-3}$ m),

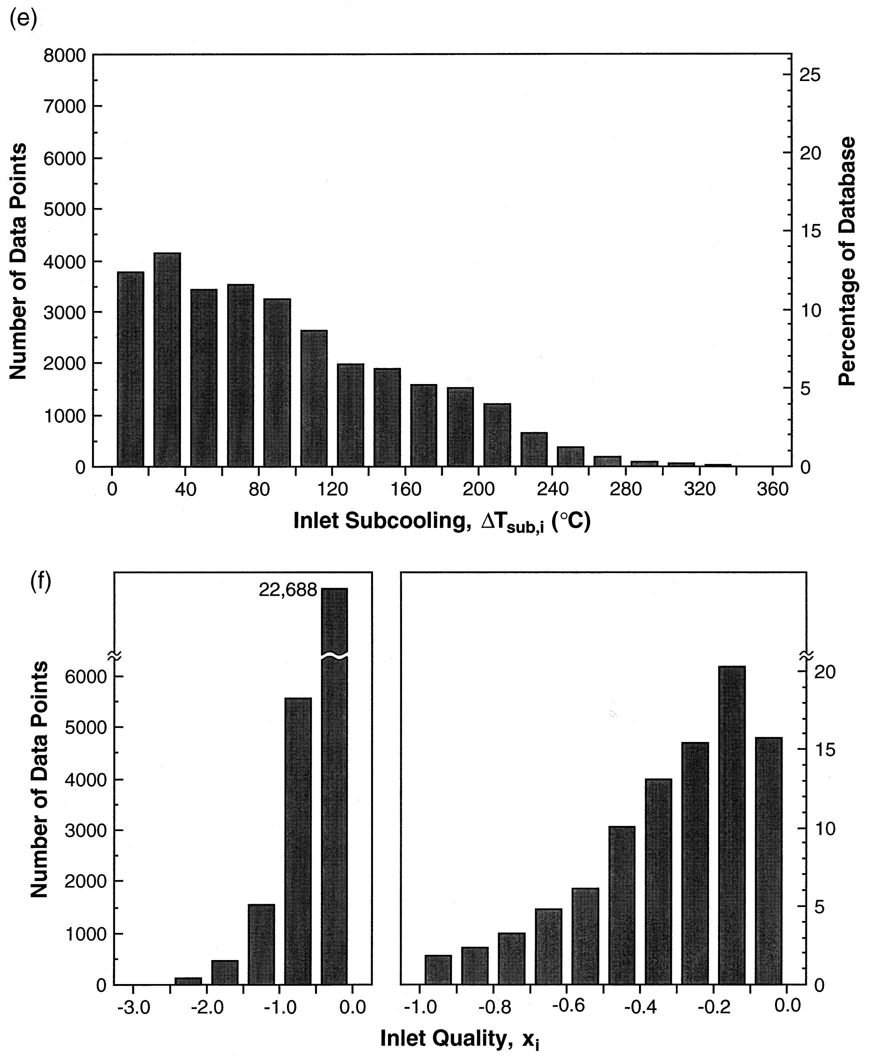


Fig. 1 (*continued*)

3. any combination of diameter and pressure appears possible,
4. subcooled outlet conditions are associated with a diameter less than 15 mm,
5. mass velocities above 40,000 kg m^{-2} s^{-1} require pressures below 30 bars,
6. saturated outlet conditions require low mass velocities ($G < 10{,}000$ kg m^{-2} s^{-1}), and
7. saturated and subcooled outlet conditions are obtained at all pressures.

Local conditions which contradict the above statements are scarce or may not be physically possible to obtain. Both Figs. 1(a)–(h) and 2(a)–(f) shows that a need does not appear to exist for additional saturated CHF data. Fig. 2(a), (c), and (e) also illustrate the need for more CHF data obtained with high mass velocity flow in a small diameter tube with a subcooled outlet; a combination of the conditions identified from Fig. 1(a)–(h).

6. Effect of tube orientation on CHF

The effect of tube orientation on CHF may be significant if the buoyancy force is not negligible compared with the axial inertial force in flow boiling. For low mass velocity flow in a horizontal tube, bubbles formed in the nucleate boiling regime migrate upwards and become concentrated in the upper section of the tube (asymmetric phase distribution). As the steam volume (and also quality) increases downstream, the bubbles coalesce and

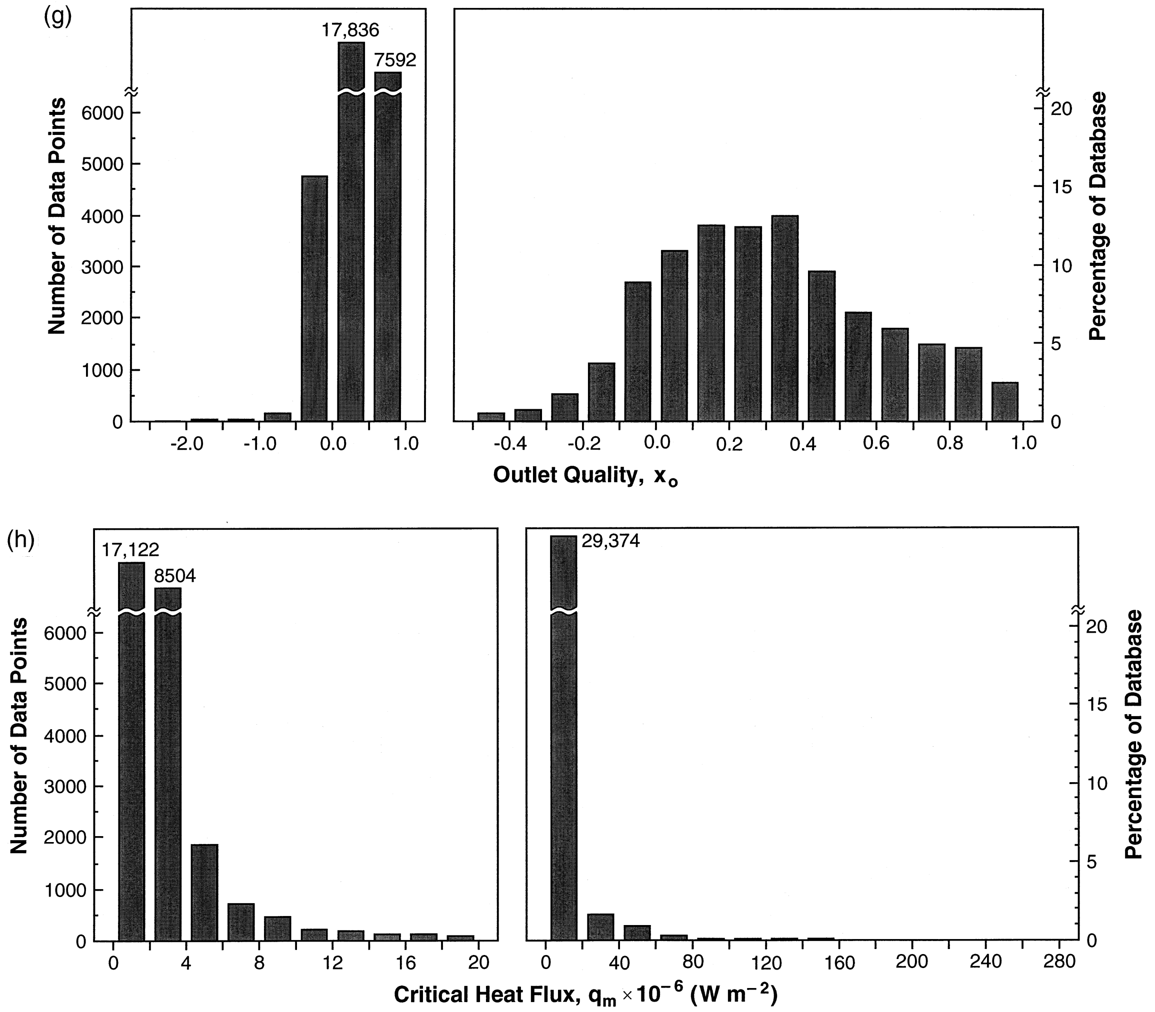


Fig. 1 (*continued*)

form a continuous vapor pocket which leads to a significant temperature rise in the top side of the tube and, consequently, a lower CHF value than that obtained with vertical upflow. Larger diameter tubes tend to promote this separation of the heavier liquid and lighter vapor phases. Higher pressures tend to hinder the phase separation since the liquid-to-vapor density ratio decreases with increasing pressure. Higher mass velocities intensify turbulent mixing, counteracting the buoyancy force and promoting a homogeneous phase distribution across the tube cross-section.

Cumo et al. [137] conducted CHF tests with Freon-12 in a variable angle test section and found that the effect of orientation on CHF diminished with increased mass velocity and was insensitive to local thermodynamic equilibrium quality. The roles of diameter and pressure were not ascertained. Nearly all of the data obtained by Cumo et al. were for saturated conditions at CHF. A criterion was developed for identifying those operating conditions where flow direction produced a noticeable deterioration in the CHF over that which was obtained in vertical upflow. A modified Froude number was defined as the ratio of the horizontal component of the inlet velocity to a term which is proportional to the bubble rise velocity,

$$Fr_* = \frac{(G/\rho_{f,i})\cos\theta}{\sqrt{gD\dfrac{\rho_f-\rho_g}{\rho_f}}}. \tag{7}$$

The tube inclination angle, θ, is measured relative to the horizontal (i.e., 0° for horizontal flow and 90° for vertical upflow). When the modified Froude number is large, say above 6 or 7, fluid stratification ceases to occur and orientation has no effect on CHF. Accord-

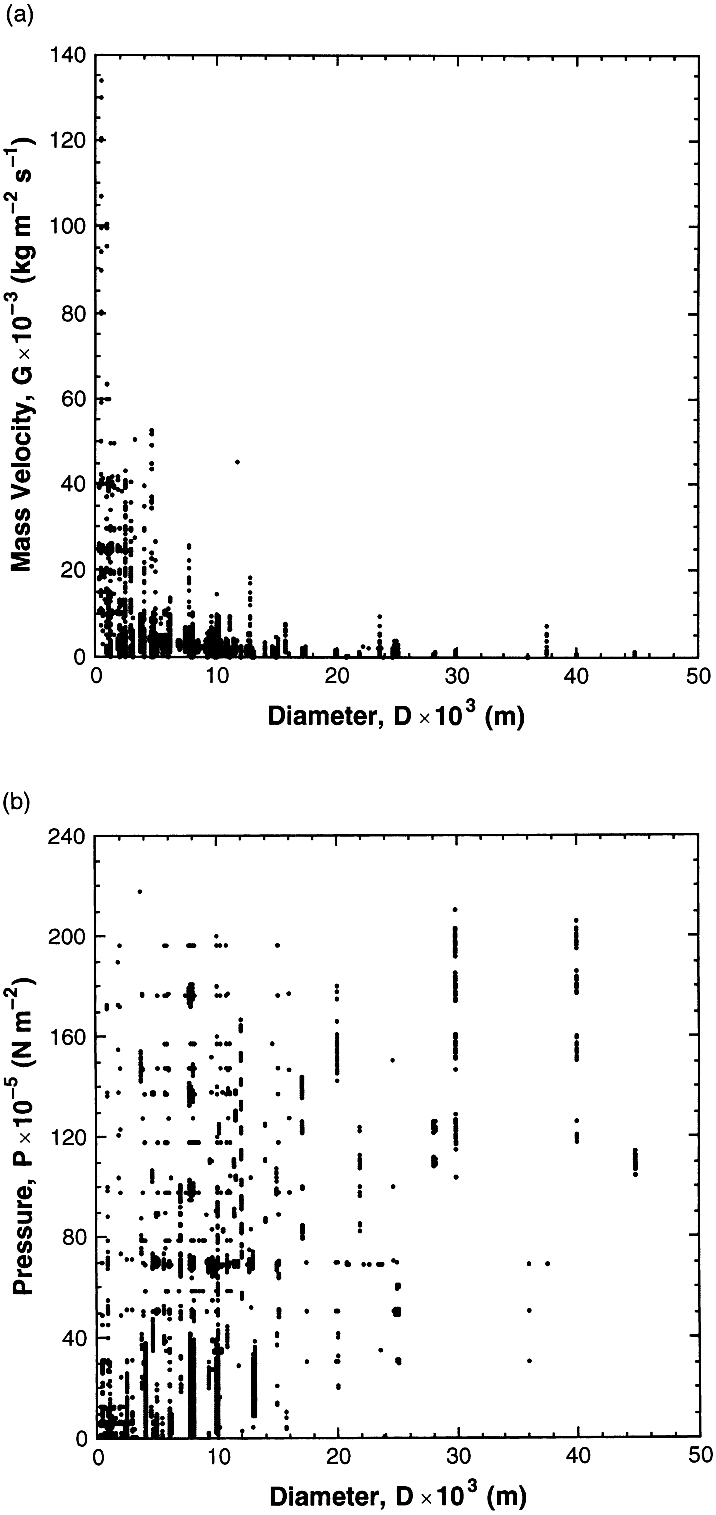


Fig. 2. Parametric distribution of data within PU-BTPFL CHF database: (a) mass velocity vs. diameter, (b) pressure vs. diameter, (c) outlet quality vs. diameter, (d) pressure vs. mass velocity, (e) outlet quality vs. mass velocity, and (f) outlet quality vs. pressure.

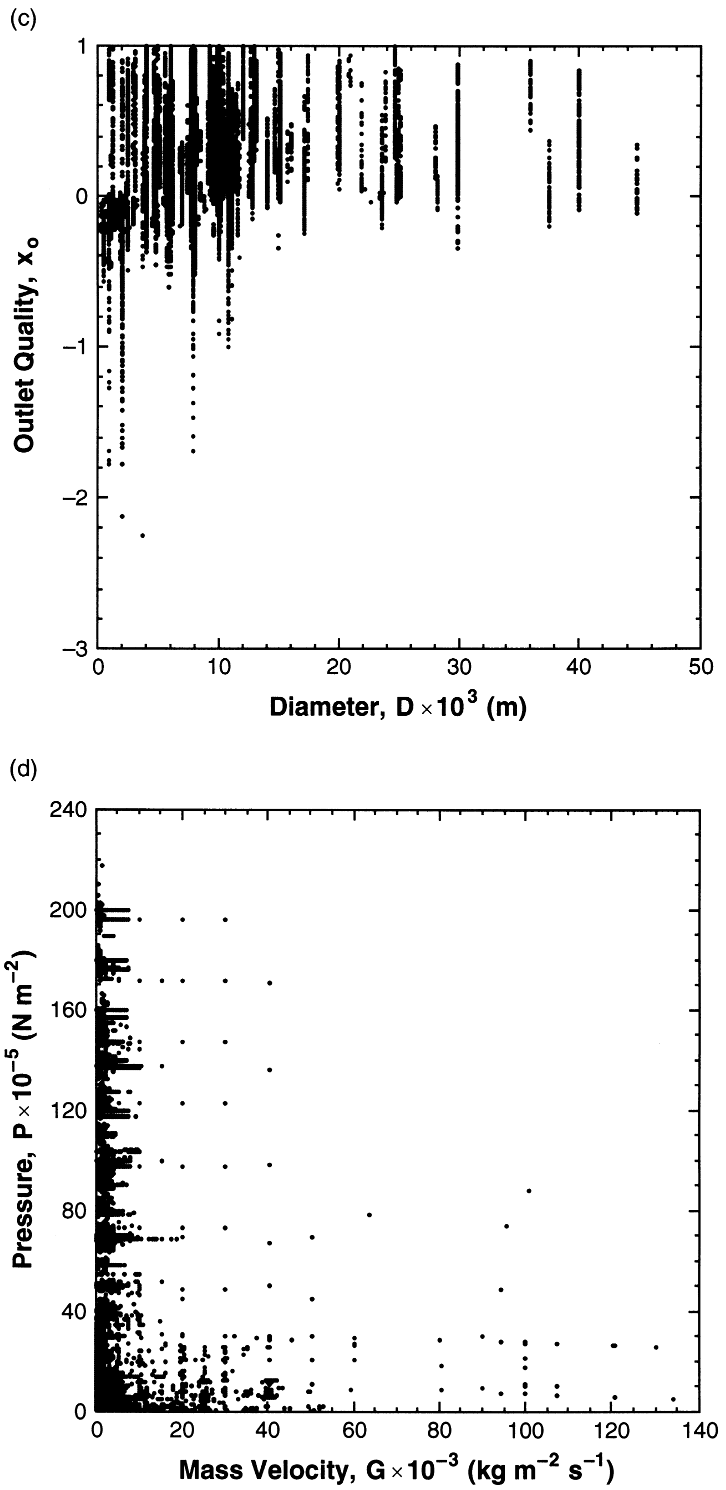


Fig. 2 (*continued*)

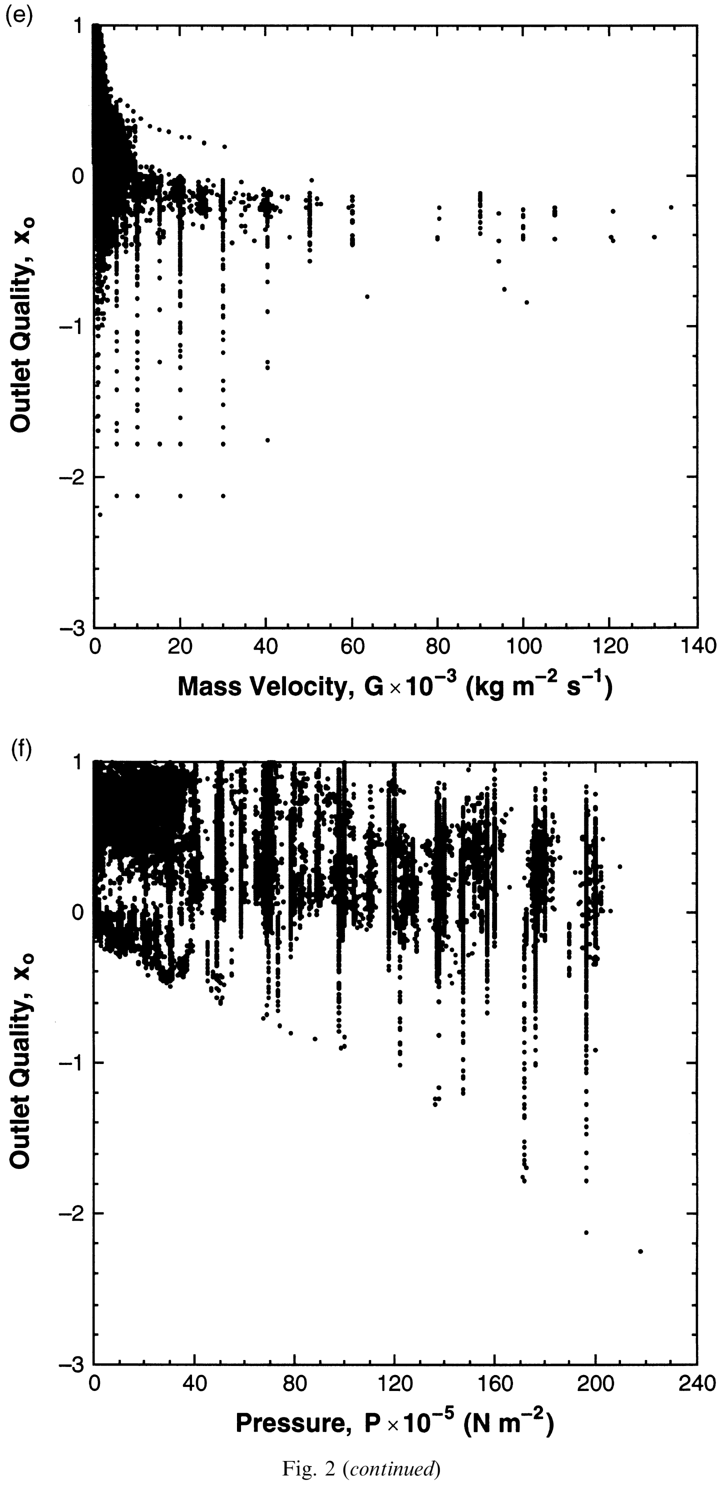


Fig. 2 (*continued*)

ing to Cumo et al., both Freon-12 and water data obtained from the open literature were well represented by this criterion.

Merilo [138] tested both Freon-12 and water in the same tube to determine the effects of fluid properties and the applicability of vertical fluid-to-fluid modeling criteria to horizontal flow. No subcooled CHF data were obtained. Again, as mass velocity decreased, the effect of orientation on CHF was more pronounced with horizontal flow yielding lower CHF values. Upstream CHF was sometimes observed with horizontal flow, but never with vertical upflow. Vertical modeling criteria were successfully applied to horizontal flow only when the effects of orientation were negligible. Merilo [138] and Merilo and Ahmad [139] concluded that, above a mass velocity of approximately 4000 kg m^{-2} s^{-1}, the difference in CHF between horizontal flow and vertical upflow was negligible for both water and Freon-12. Furthermore, Waters et al. [61] obtained CHF data above a mass velocity of 6460 kg m^{-2} s^{-1} and found no difference between horizontal flow and vertical upflow. However, Becker [116] found that CHF values for vertical upflow and horizontal flow of water were similar even at a much lower mass velocity than that specified by Merilo and Ahmad. For pressures between 10 and 30 bars, Becker concluded that the transitional mass velocities for 9.95 and 12.9 mm diameter tubes were 350 and 460 kg m^{-2} s^{-1}, respectively, for saturated conditions at CHF. Below these mass velocities, upstream CHF occurred with horizontal flow and the resulting CHF values were much lower than that obtained with vertical upflow. Merilo also recommended using the adiabatic flow pattern map for horizontal flow from Taitel and Dukler [140]. The transition between intermittent (slug or elongated bubble) flow and dispersed bubble flow was postulated to correspond to the transition in a low quality flow from a region where orientation is important to where it is unimportant.

Jensen and Bergles [141] focused their study on the differences in subcooled CHF between R-113 flow in a straight, horizontal tube and a helically coiled tube with a vertical coil axis. Local thermodynamic equilibrium qualities ranged from −0.4 to 0.3 for horizontal flow CHF. Low mass velocity, horizontal CHF data were compared with a correlation developed using high mass velocity, horizontal CHF data. A correction factor based on the ratio of bubble buoyancy to inertia forces was utilized to account for the buoyancy-induced degradation in CHF,

$$K_{\mathrm{hor}} = \begin{cases} 1.0 & Ga/Re_D^2 < 0.0127 \\ 0.4\left(Ga/Re_D^2\right)^{-0.21}, & Ga/Re_D^2 \geq 0.0127, \end{cases} \tag{8}$$

where the tube diameter was used instead of the bubble diameter, thus referring to the onset of plug flow. This ratio was originally employed by Bertoni et al. [142] to examine the effect of buoyancy in vertical downflow. A correction factor near one means buoyancy forces are relatively small and the CHF value obtained in horizontal flow is similar to that obtained in vertical upflow. Note that Jensen and Bergles incorrectly used a modified Grashof number containing vapor viscosity instead of the Galileo number, resulting in a ratio different from that specified in Bertoni et al.

Wong et al. [143] developed a CHF prediction method for horizontal flow using correction factors applied to vertical upflow CHF data or correlations. The correction factor is strongly dependent on the flow regime. This method replaced a simpler method from Groeneveld et al. [9]. Since the new method is quite complex and mainly applicable to saturated conditions and the annular flow regime, it will not be discussed in the present study. Furthermore, Wong et al. did not provide a clear recommendation for determining the correction factor in bubbly flows (i.e., subcooled conditions).

The transitional mass velocity below which orientation effects CHF is often different, depending upon the fluid, tube diameter, or pressure [61,116,138,139]. Thus, this criterion cannot easily be used with a large CHF database. The authors of the present study recommend using Eqs. (7) and (8) for determining if orientation has an effect on CHF. The criteria $Fr_* < 6$ and $K_{\mathrm{hor}} < 0.9$ were used to identify those horizontal, subcooled CHF data which were affected by orientation. Only 24 of 633 data points violated both of these criteria. However, these data were not excluded from the database on the basis that the criteria were developed mainly with saturated CHF data and that a subcooled CHF correlation [129] with proven accuracy predicted their CHF values with the same accuracy as the remainder of the horizontal data. An analysis of the effect of orientation on the saturated CHF data is beyond the scope of the present study.

7. Summary

The present study was motivated in part by the lack of a large, reliable, error-free CHF database for developing and validating CHF correlations and mechanistic models. The Purdue University-Boiling and Two-Phase Flow Laboratory (PU-BTPFL) CHF database for vertical upflow and horizontal flow of water in a uniformly heated tube was compiled from the world literature dating back to 1949 and represents the largest CHF database ever assembled with 32,544 data points from over 100 sources. The superiority of the database was ensured by compiling CHF data only from original sources and by carefully examining the data on a point-by-point basis. The database is an invaluable tool for the development of CHF correlations and mechanistic models that are superior to existing ones developed with smaller, unreliable CHF databases. The database is available to researchers worldwide in hard copy form and on CD-ROM in order to facilitate cost effective research on the CHF phenomenon. Other accomplishments resulting from the compilation and assessment of this database are as follows:

1. Previous CHF databases for water flow in a uniformly heated tube were critically examined and discovered to contain an abundance of duplicate and unusable data. The majority of imperfections found in these databases were attributed to the authors inadvertently tabulating data from older databases and not from the original source of the data. CHF correlations and models developed or validated using these databases are questionable and must be re-evaluated using a large, reliable CHF database.
2. Recommendations were provided for acquiring and publishing CHF data in a manner that is useful in the development or refinement of CHF correlations and models. Also, experimental conditions for which little or no CHF data presently exist were identified by examining the parametric distribution of data within the PU-BTPFL CHF database. Future experimental programs should focus on flow in tubes having a diameter less than 5 mm and a mass velocity above 10,000 kg m^{-2} s^{-1}, which most likely corresponds to subcooled CHF conditions and relatively high CHF values. Additional saturated CHF data will not significantly enhance the database.
3. Guidelines were established for identifying horizontal flow CHF data which were affected by tube orientation.

Acknowledgements

The authors are grateful for the support of the Office of Basic Energy Sciences of the US Department of Energy (Grant No. DE-FG02-93ER14394.A003). Financial support for the first author was also provided in the form of the Link Foundation Energy Fellowship and the Ingersoll-Rand Fellowship.

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